Selected Aerothermodynamic Design Problems of Hypersonic Flight Vehicles

Ernst Heinrich Hirschel · Claus Weiland

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Preface

Hypersonic flight and aerothermodynamics are fascinating topics. Design problems and aerothermodynamic phenomena are partly very different for the various kinds of hypersonic flight vehicles. These are—and will be in the future—winged and non-winged re-entry vehicles as well as airbreathing cruise and acceleration and also ascent and re-entry vehicles.

Both authors of the book worked for almost four decades in hypersonics: at the German aerospace research establishment (DVL/DFVLR, now DLR) to the end of the 1970s, then in industry (MBB/Dasa, now EADS). They were involved in many major technology programs and projects. First, in the early 1970s, the German ART program (Association for Re-Entry Technologies), and, in the 1980s, the European (ESA) HERMES project and the German Hypersonics Technology (SÄNGER) program. Then followed, in the 1990s, the Future European Space Transportation Investigations program (FESTIP), the Manned Space Transportation program (MSTP) with the Atmospheric Re-Entry Demonstrator (ARD), the X-CRV Project with the X-38 vehicle and, later, the German technology programs TETRA (Technologies for Future Space Transportation Systems), ASTRA (Selected Systems and Technologies for Future Space Transportation Systems Applications), and IMENS (Integrated Multidisciplinary Design of Hot Structures for Space Vehicles).

Research in the 1960s and 1970s placed great emphasis on low-density flows, high temperature real gas effects in ground-simulation facilities and, already, on discrete numerical computation methods. After the first flights of the Space Shuttle Orbiter with its generally very good aerodynamic performance, interest in low-density problems diminished. The layout of the thermal protection systems highlighted the importance of high temperature real gas effects, surface catalycity and laminar–turbulent transition. Numerical methods received a large boost first during post-flight analyses of the Orbiter flights and then, in particular in Europe, during the research and development activities accompanying the HERMES project.

A serious problem showed up during the first Orbiter flight, viz., the hypersonic pitching moment anomaly, which gave rise to grave concerns in the HERMES project. This new vehicle had a shape totally different to that of the Orbiter. The question was whether similar or other problems—undetected in the vehicle design—would become manifest during flight. Because the hypersonic pitching moment anomaly was obviously a ground facility simulation problem, much emphasis was put on the development and application of numerical methods and their validation. Consequently, an experimental vehicle was proposed, the 1:6 down-scaled MAIA. The first author of this book was deeply involved in the definition of its scientific payload although neither MAIA nor HERMES actually flew.

Work in the SÄNGER program revealed that viscous effects dominate airbreathing hypersonic flight rather than pressure or compressibility effects as is the case in re-entry flight. Viscous thermal surface effects of all kinds, governed by surface radiation cooling became a major focal point in hypersonic research and design work. These are important subjects covered in a previous publication by the first author on the basics of aerothermodynamics.

The fantastic increase in computer power in the second half of the 1990s showed that it will be possible in future to treat the many strong couplings between the disciplines involved in the design of hypersonic flight vehicles in new ways. Multidisciplinary numerical simulation and optimization methods became a major focus in ASTRA and IMENS, in which the second author was strongly involved.

All these findings and developments, together with the responsibility of the first author for an initial structuring of general medium and long-term technology development and verification strategies in both the SÄNGER technology program and FESTIP, have shaped the content of the present book. It discusses selected aerothermodynamic design problems of winged and non-winged re-entry and airbreathing hypersonic flight vehicles—but not the full vehicle design.

The work and experience of the authors are reflected in the chapters on winged re-entry vehicles (RV-W's), airbreathing cruise and acceleration vehicles (CAV's) and non-winged re-entry vehicles (RV-NW's). Besides the major aerothermodynamic phenomena and simulation problems, particular trends in aerothermodynamics of these vehicle classes are discussed.

Special attention is paid to the hypersonic pitching moment anomaly of the Space Shuttle Orbiter and to forebody aerothermodynamics of airbreathing vehicles. Furthermore, there is a comprehensive presentation of waverider design issues. For non-winged re-entry vehicles, trim and dynamic stability issues are discussed. In particular, aerothermodynamic issues of stabilization, trim and control devices are also considered.

The authors' research, university teaching and industrial involvement have shown that it is important to cover topics that are usually not in the major focus of books on aerothermodynamics. These are the fundamentals of flight trajectory mechanics, including the general equations for planetary flight, the describing mathematical equations in general formulation of forces, moments, center of pressure, trim and stability, as well as multidisciplinary design aspects including the mathematical models and the coupling procedures.

Another outcome of the authors' work was the recognition that it would be useful to provide the reader with quantitative examples of the coefficients of—at least—longitudinal motion for a variety of shapes of operational vehicles, demonstrators, and studied concepts. In this way, numbers are available to compare and to check the results of the readers own work. Many of the data that we provide were generated with both numerical simulations and experimental tests in the department formerly headed by the second author.

Although the thermal state of a vehicle surface and the ensuing thermal loads and thermal surface effects are among the major topics of hypersonic vehicle design, they are not treated separately in this book. Their treatment is integrated in the corresponding chapters. However, a short overview of the basic issues, as well as a simulation compendium, is given in a separate chapter.

Both authors have advanced over many years the use of discrete numerical methods of aerothermodynamics in research and in industrial applications. These methods now permit a thorough quantification of and deep insights into design problems and the relevant aerothermodynamic phenomena. A good overall knowledge is necessary for their successful application, as is an eye for the relevant features. Consequently, this book discusses in great detail results of numerical simulations, also in view of the multidisciplinary implications of aerothermodynamics.

The book is intended for graduate students, doctoral students, design and development engineers, and technical managers. A useful prerequisite is a knowledge of the basics of aerothermodynamics.

We see presently an up and down of the different modes and vehicles of hypersonic flight. Non-winged concepts now seem to displace winged re-entry concepts. Airbreathing hypersonic flight is a concept still waiting for its time. Nevertheless, we are convinced that hypersonic flight has a bright future. We hope that our book will help the reader to make himself familiar with a number of problems regarding the aerothermodynamic design of hypersonic flight vehicles.

April 2009

Ernst Heinrich Hirschel
Claus Weiland

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Claus Weiland

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1

Introduction

When studying papers discussing aspects of the aerodynamic shape definition process of the Space Shuttle Orbiter, see, e.g., [1], one is confronted with a host of different methods, correlations, simulation tools, etc. which were employed. At that time the discrete numerical methods of aerodynamics and aerothermodynamics were just beginning to appear. In the meantime very large algorithmic achievements and fantastic developments in computer speed and storage, and in general in the information technologies, have happened and change now profoundly the aerothermodynamic design processes, but also the scientific work.

However, numerical methods, like ground-simulation facilities, are "only" tools. Basic knowledge of both aerothermodynamic phenomena and design problems are the prerequisites which must be present in order to use the tools effectively. It is important to note in this context, that extended design experience for space transport vehicles, backed by flight experience, is available only from the Space Shuttle Orbiter as well as from the capsules APOLLO and SOYUZ.

The Space Shuttle Orbiter is a winged re-entry flight vehicle which has its specific aerothermodynamic phenomena and design problems. If one looks at airbreathing hypersonic flight vehicles, the picture is radically different. Re-entry vehicles on purpose have large drag, while airbreathing flight vehicles must have a drag as low as possible, which immediately brings into play the viscous drag and many aerothermodynamic phenomena and design problems other than those present or important for the Space Shuttle Orbiter.

It is even apt to distinguish between hypersonic flight and hypersonic flow. A winged re-entry vehicle flies at hypersonic speed, but usually the flow in the shock layer is in the subsonic to low supersonic speed domain. An airbreathing flight vehicle flies at hypersonic speed, but now the flow past the vehicle is a true hypersonic flow. This implies that *hypersonics* in one case can be a topic vastly different from *hypersonics* in another case [2].

In this book we treat selected aerothermodynamic design problems of predominantly hypersonic flight vehicles operating in the Earth atmosphere at altitudes $H \lessapprox 100$ km and flight velocities $v_\infty \lessapprox 8$ km/s. We do not attempt to cover the issue of overall aerothermodynamic vehicle design, but to explain, demonstrate and illustrate design problems. Because of the partly very different vehicle shapes and the different flow phenomena present, a classification of the flight vehicles into winged re-entry vehicles, airbreathing cruise and acceleration vehicles, and non-winged re-entry vehicles, i.e. space capsules, like given in [2], is employed.

This classification is sketched first, then we discuss shortly aerothermodynamics and the definition and development of flight vehicles with regard to design sensitivities, design margins, data uncertainties, and the potential and deficits of simulation means. The latter also appears to be necessary, because design problems usually are coupled to simulation problems, too. Sometimes even a design problem is "only" a simulation problem. This chapter is closed with a sketch of the scope and the content of the book.

1.1 Three Reference Classes of Hypersonic Vehicles

Winged re-entry vehicles (RV-W), airbreathing cruise and acceleration vehicles (CAV), and non-winged re-entry vehicles or space capsules (RV-NW) are chosen to be the reference flight vehicle classes in this book. In [2] the class of ascent and re-entry vehicles (ARV) is added. ARV's in principle are single-stage-to-orbit (SSTO) space transportation systems with airbreathing (and rocket) propulsion. In a sense the design problems of these vehicles are a mixture of the problems encountered for RV-W's and CAV's. Therefore, we do not treat this class here separately. In [2] aeroassisted orbital transfer vehicles (AOTV) are introduced as a separate class to serve as a kind of extreme reference vehicle class. We do not treat this class either but have introduced instead the class of RV-NW's with their operation, like that of the other classes, predominantly in the $H \lessapprox 100$ km and $v_\infty \lessapprox 8$ km/s domain.

For more details regarding vehicle classifications see [2] and for a very detailed classification, e.g., [3]. The vehicles of the three reference classes referred to in the accordant chapters are:

1. Winged re-entry vehicles (RV-W's): Space Shuttle Orbiter, HERMES, HOPE-X, X-34, X-38, and HOPPER/PHOENIX. RV-W's are launched typically by means of rocket boosters, but potentially also as rocket-propelled upper stages of two-stage-to-orbit (TSTO) space transportation systems.
2. Cruise and acceleration vehicles with airbreathing propulsion (CAV's): the lower stage of the TSTO system SÄNGER, and also the ARV Scram 5. Flight Mach numbers lie in the ramjet propulsion regime up to $M_\infty = 7$, and the scramjet propulsion regime up to $M_\infty = 12$ (to 14).
3. Non-winged re-entry vehicles (RV-NW's), some of them not operating in the Earth atmosphere: HUYGENS, BEAGLE2, OREX, APOLLO, ARD, SOYUZ, VIKING, AFE, CARINA and others.

Each of the three classes has specific aerothermodynamic features which are summarized in Table 1.1 (see also [2]).

Table 1.1. Comparative consideration of particular aerothermodynamic features of the three reference classes of hypersonic vehicles. Features which are common to all classes are not listed.

Item	Winged re-entry vehicles (RV-W's)	Cruise and acceleration vehicles (CAV's)	Non-winged re-entry vehicles (RV-NW's)
Mach number range	30–0	0–7(12)	30–0
Configuration	blunt	slender	very blunt, blunt
Flight time	short	long	short
Angle of attack	large	small	head on
Drag	large	small	large
Aerodynamic lift/drag ratio	small	large	small, zero
Flow field	compressibility-effects dominated	viscosity-effects dominated	compressibility-effects dominated
Thermal surface effects: 'viscous'	not important/ locally important	very important	not important
Thermal surface effects: 'thermo-chemical'	very important	important	very important

Without a quantification of features and effects we can say that for CAV's viscosity effects, notably laminar–turbulent transition and turbulence (which occur predominantly at altitudes below approximately 60 to 40 km) play a major role, while high temperature real gas (thermo-chemical) effects are very important for RV-W's and RV-NW's. Viscous thermal surface effects play a large role for CAV's, while thermo-chemical thermal surface effects are very important for RV-W's and RV-NW's [2].

The main objective of Table 1.1 is to sharpen the perception, that for instance a CAV, i.e. an airbreathing hypersonic flight vehicle, definitely poses an aerothermodynamic (and multidisciplinary) design problem quite different from that of a RV-W. The CAV is aircraft-like, slender, flies at small angles of attack, all in contrast to the RV-W. The RV-W is a pure re-entry vehicle, which is more or less "only" a deceleration system, however not a ballistic or quasi-ballistic one as is the RV-NW. Therefore it has a blunt shape, and flies at large angles of attack in order to increase the effective bluntness.

Thermal loads must always be considered together with the structure and materials concept of the respective vehicle, and its passive or active cooling concept. As discussed in [2], the major passive cooling means for outer surfaces is surface-(thermal-)radiation cooling. The thermal management of a CAV, for instance, must take into account all thermal loads (heat sources), cooling needs and cooling potential of the airframe, propulsion system, subsystems and cryogenic fuel system.

1.2 Aerothermodynamics and the Definition and Development of Flight Vehicles

High performance and at the same time high cost efficiency of all kinds of hypersonic flight vehicles will most likely not be achieved by single large technological breakthroughs. A good chance exists that they will be achieved in the future, at least partly, by better, more accurate and more versatile disciplinary and multidisciplinary numerical simulation and optimization tools in all vehicle definition and development phases and processes. This certainly is possible, when we observe how discrete numerical methods in all involved technology areas advance, supported by the vast growth of computer power. A similar development is underway in classical aircraft design [4]-[6].

In view of this prospect we think it is useful to look at some important aspects of vehicle design and development, in particular with respect to design sensitivities and margins, and accounting for data uncertainties and deficits of aerothermodynamic simulation means.

1.2.1 Design Sensitivities and Margins versus Data Uncertainties

In [2] the term "simulation triangle" is used. The simulation triangle consists of computational simulation, ground-facility simulation and in-flight simulation. None of the simulation means in the triangle permits a full simulation of the aerothermodynamic properties and functions of hypersonic flight vehicles, Section 1.2.2. It is the art and experience of the engineer to arrive nevertheless at a viable aerothermodynamic design. However, in future the engineer will command much more powerful numerical simulation and optimization tools than he has available today.

In the following a short consideration of the three important entities in the definition and development processes, "sensitivities", "uncertainties", and "margins", is given, following [2]. For a discussion of design methodologies of hypersonic flight vehicles as we consider them in this book, see, e.g., [7]-[9].

The objectives of the definition and development processes are:

– the design of the flight vehicle with its performance, properties and functions according to the specifications,
– the provision of the describing data of the vehicle, the vehicle's data sets.

The aerodynamic design is embedded in the design of the whole flight vehicle [10]. A few decades ago the tools typically used in the aerodynamic shape definition were approximate and parametric methods, and for aerodynamic verification purposes, data set generation and problem diagnosis the ground-simulation facilities [5]. This has changed insofar as numerical methods now have a very important role in all tasks of aerodynamics and aerothermodynamics.

In view of the whole vehicle design, sensitivities and margins with respect to data uncertainties are of general interest:

Design sensitivities are sensitivities of the flight vehicle with regard to its performance, properties and functions. Hypersonic airbreathing flight vehicles (CAV) are, for instance, sensitive with regard to vehicle drag (the "thrust minus drag" problem), and quite in general, with regard to aerothermodynamic propulsion integration. We state:

- small design sensitivities permit rather large uncertainties in describing data (vehicle data sets),
- large design sensitivities demand small uncertainties in the describing data sets.

Uncertainties in describing data are due to deficits of the simulation means, i.e. the prediction and verification tools:

- computational simulation, there especially flow-physics and thermo-chemical models,
- ground-facility simulation,
- in-flight simulation.

Design margins finally allow for uncertainties in the describing data. The larger the uncertainties in design data, for given sensitivities, the larger are the design margins, which have to be employed in the system design. They concern for instance flight performance, flight mechanics, etc. Design margins potentially give away performance. In general, uncertainties in describing data (particularly where sensitivities are large) should be reduced in order to reduce design margins. Of course it is desirable to keep design sensitivities as small as possible, but demands of high performance and high cost efficiency of flight vehicles will always lead to large design sensitivities. Reduced uncertainties in describing data reduce design risks, cost and time [6].

1.2.2 Deficits of Aerothermodynamic Simulation Means

A discussion of the potentials and deficits of the aerothermodynamic simulation means is given in [2] and in this book in the form of an aerothermodynamic simulation compendium in Section 9.3. We give here a more general overview of the most important deficits of simulation means, because they are the sources of uncertainties in the describing data and hence are governing the design margins, presenting large challenges to the designer and developer.

The discrete numerical methods of aerothermodynamics have become an important tool in research and in industrial design. They permit, in principle, to simulate all aerothermodynamic phenomena and design problems including the thermal state of flight vehicle surfaces in the presence of surface radiation cooling.[1] The discrete numerical methods suffer, however, as other computational simulation tools, from deficits in thermo-chemical models and even more so in flow-physics models (laminar–turbulent transition, turbulence, turbulent flow separation).

These deficits and the still not large enough computer power limit computational simulation basically to the design process and to diagnosis issues. Full-fledged data set generation on the computer is still years away, because of the relatively small productivity of numerical simulation compared to ground-simulation facilities.[2] However, the treatment of multidisciplinary design and development problems is becoming more and more a key application domain of aerodynamic/aerothermodynamic numerical methods. This is important in view of the waning of Cayley's design paradigm [6], also Chapter 8 of the present book, especially for airbreathing CAV's.

Ground-facility simulation has some principle deficits which cannot be overcome. In general a full experimental simulation of reality, particularly of thermal surface effects in the presence of surface radiation cooling, is not possible in ground-simulation facilities. The simulation of laminar–turbulent transition is another very critical topic. For aerothermodynamic investigations of RV-W's and RV-NW's a strong reliance seems to exist on the Mach number independence principle of Oswatitsch, which however usually is not explicitly stated. High-enthalpy facilities attempt to overcome freezing phenomena in the nozzle by employing ever higher reservoir densities, but introduce other problems. For CAV's especially viscous thermal surface effects cannot be treated properly in wind tunnels. In the aerothermodynamic design process the verification and data set generation is affected by deficits which lead again to uncertainties of the describing data.

The matter of productivity of simulation means especially for aerodynamic data set generation demands a closer consideration. Up to now only one winged hypersonic flight vehicle (RV-W) became operational, the Space Shuttle Orbiter. Due to the very commendable publication policy of the NASA

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1 The thermal state of a surface is defined by both the wall temperature T_w and the heat flux in the gas at the wall q_{gw}, Chapter 9. It governs viscous and thermo-chemical thermal surface effects as well as the thermal loads (aeroheating) on the surface.

2 Although computation speed on certain computer architectures now is in the Teraflops (10^{12} floating-point operations per second) domain, this is by far not fast enough to beat productivity of (not all, see below) ground-simulation facilities, once a suitable model has been fabricated and instrumented. Note, however, that a computational solution is usually much richer than the set of measured data.

(see, e.g., [11, 12]), we can study in detail the development and design experience gained with this vehicle.[3]

We quote first W.C. Woods and R.D. Watson [13] regarding the Space Shuttle Orbiter design and development: *In general, configuration screening was conducted in NASA's hypersonic research facilities (relatively small, inexpensive blowdown tunnels) and benchmark performance, stability and control characteristics in hypersonic continuum flow were determined in the Department of Defence's relatively large hypersonic facilities.* The latter facilities are the Arnold Engineering and Development Center (AEDC) Supersonic Tunnel A and Hypersonic Tunnel B, and the Naval Surface Warfare Center Hypervelocity Tunnel 9.

Why these tunnels? They are, on the one hand, capable of simultaneous Mach number and Reynolds number simulation, though only with perfect gas flow, and on the other hand, they have a high productivity. They are continuous (Tunnel A and B) and blowdown (Tunnel 9) facilities, [14], the latter with testing times large enough to permit the pitch pause or the continuous sweep approach[4] to measure in one run a polar in the $\alpha = 0°$ to $45°$ range. In contrast to this a high-enthalpy pulse facility will permit at most a few "shots" per day. If being in a mile-stone driven project, this will be intolerable nowadays, as it was during the Space Shuttle project. The Space Shuttle Orbiter approach worked well, except regarding the pitching moment at hypersonic speeds (STS-1), see Section 3.5. It is to be expected that for possible future developments of RV-W's this approach will be followed again, although now with very heavy support by numerical aerothermodynamics.

In view of thermal loads the lessons learned with the Space Shuttle Orbiter regarding the matter of productivity is somewhat different from that regarding aerodynamic data [15]. In any case also large data sets need to be produced to cover the potential flight trajectories of a re-entry vehicle, including abort trajectories, with a multitude of trim and control surface settings.[5] A special problem are various types of gap flows and leak flows. Also in the future ground-facility simulation will bear the main load, although with heavy support by numerical aerothermodynamics.

The reader should note that for CAV's no experience is available regarding productivity of ground-simulation means as exists for RV-W's. Regarding RV-NW's the situation is rather good, Chapter 5, although no problems as severe

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[3] The Russian BURAN flew once and also several American and Russian experimental vehicles, however the wealth of the material available from the Space Shuttle Orbiter is unparalleled.

[4] In these approaches the wind tunnel model is intermittently or slowly moving from one angle of attack to the other (pitch pause) or continuously (continuous sweep) through the preset angle of attack domain.

[5] Aerodynamic control surfaces can be multi-functional. In the case of the Space Shuttle Orbiter the elevons are used to control trim, pitch, and roll. The body flap as main trim surface was originally intended only to act as a heat shield for the main engine nozzles.

as the hypersonic pitching moment problem of the Space Shuttle Orbiter (STS-1) have been observed so far.

In-flight simulation basically is centered on experimental and demonstration issues, which cannot be dealt with sufficiently on the ground. Large design sensitivities and deficits in the ground-simulation means may make extended in-flight simulation and testing necessary for future projects with large technology challenges.

An issue often overshadowed by simulation issues (fidelity, uncertainties, apparatus, cost and time) is simply the understanding of a given design problem and the involved phenomena. It is very important for a designer to know the implications of phenomena for the design problem at hand, and for the engineer to know the implications for simulation problems and for diagnostic (trouble shooting) purposes. A prerequisite of understanding in this sense is a good knowledge of the physical basics. Understanding can sometimes be achieved with simple analytical considerations which yield basic trends and also order of magnitude knowledge of an effect.

1.3 Scope and Content of the Book

When treating selected aerothermodynamic design issues in this book, our goal is to obtain an understanding of the problems at hand, to show how they are related to flight vehicle or vehicle component functionality and performance, to isolate relevant phenomena and their interdependencies, and to give quantitative information. We do not intend to deal with overall configuration design, or detailed aerothermodynamic configuration definition.

The aerodynamic and aerothermodynamic design of flight vehicles presently is undergoing large changes regarding the tools used in the design. Discrete numerical methods have become mature tools (even if partly still restricted by shortcomings in flow-physics and thermo-chemical models). Therefore mostly results of numerical aerothermodynamics will be presented and discussed, simply because they usually contain detailed information which otherwise is not easy to obtain.

In the following Chapter 2 we give a short introduction to flight trajectories for aerothermodynamicists including a full presentation of the general flight mechanical equations for planetary flight. The constraints, which result from the flight trajectories for the aerothermodynamic design and vice versa, should be understood at least in a basic way. Chapter 3 deals with selected aerothermodynamic design problems of winged re-entry (RV-W) flight vehicles. General aerothermodynamic issues of these vehicles are discussed first, together with particular aerothermodynamic trends. It follows a presentation and discussion of available aerodynamic performance data (coefficients of longitudinal motion) of a number of RV-W shapes. Finally issues of vehicle flyability and controllability, in particular the hypersonic pitching moment anomaly, observed during the first flight of the Space Shuttle Orbiter, are discussed.

A similar range of topics is treated in Chapter 4 for winged airbreathing flight vehicles (CAV's), there especially also issues of aerothermodynamic airframe/propulsion integration and of waverider design, and in Chapter 5 for re-entry capsules (RV-NW's). For a couple of the capsules aerodynamic data sets of longitudinal motion are given, together with an in-depth discussion of the role of the z-offset of the center-of-gravity and nominal and parasite trim.

Chapter 6 is devoted to a thorough presentation of aerothermodynamic design problems of stabilization, trim and control devices, which to a large extent are the same for all vehicle classes considered in this book. In Chapter 7 general formulations are given of forces, moments, center of pressure, trim, and stability of flight vehicles. These, like the flight mechanical equations in Chapter 2 usually are not found in a general form in the literature.

Chapter 8 is devoted to a discussion of multidisciplinary design aspects which are of interest for hypersonic vehicle design. Also in this evolving discipline the describing equations in a general form are seldom found in the literature, which also holds for the coupling procedures. Few application examples are available so far from hypersonic vehicle design.

The thermal state of a vehicle surface and the ensuing thermal loads and thermal surface effects are of large interest in aerothermodynamic vehicle design. Nevertheless, we do not treat them separately in this book, but integrate them in the corresponding chapters. However, a short overview of the basic issues, as well as a simulation compendium, is given in Chapter 9, together with a compilation of the most important approximate relations used or referred to in the book in Chapter 10. A solution guide to the problems is given in Chapter 11.

The full governing equations for flow with high temperature real gas effects are presented in Appendix A. The properties of the Earth atmosphere are given in Appendix B. They should provide the reader quickly with data especially also for the solution of the problems which are provided at the end of several of the chapters. The book closes with constants, units and conversions, Appendix C, symbols, Appendix D, a glossary, abbreviations and acronyms, Appendix E, and, following the acknowledgement of copyright permissions, the author and the subject index.

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2

Short Introduction to Flight Trajectories for Aerothermodynamicists

Aerothermodynamic design, aerothermodynamic phenomena, and the choice of flight trajectories of either re-entry vehicles, space-transportation systems or hypersonic aircraft depend mutually on each other. We give here a short introduction to issues of flight trajectories in order to provide basic knowledge about these dependencies.

The very fast flight of hypersonic vehicles, partly with vast changes of the flight altitude, makes a precise flight guidance necessary. This is especially a problem with CAV-type space transportation systems because of their very small pay-load fractions. The basic problem is to find a flight trajectory which permits the vehicle to fulfill its mission with minimum demands on the vehicle system. However, different from classical aircraft design, the physical properties and the functions of a hypersonic vehicle and its components must be extremely closely tailored to the flight trajectory and vice versa.

To design and to optimize a vehicle's flight trajectory in a sense is to solve a guidance problem. While the fulfillment of the basic mission is the primary objective of the trajectory definition, other, secondary objectives may exist. In the multi-objective design and optimization of a trajectory, these must be identified as **guidance objectives**. It is further necessary to define and to describe the **trajectory control variables**, which permit the vehicle to fly the trajectory. Finally, a system reduction is necessary to identify a few characteristic physical loads and vehicle properties/functions, whose limitations and/or fulfillments are introduced as **systems and operational constraints** in the trajectory design and optimization process. The eventual outcome are **guidance laws**, which in general have a rather small number of free parameters to fulfill the mission objectives under the given conditions.

Prerequisites for trajectory design and optimization are flyability and controllability of the considered vehicle on the sought trajectory. Under flyability we understand longitudinal trimmability, and static and dynamic stability, which, with a few exceptions, is the rule for both the longitudinal and the lateral motion of the vehicle. Controllability is the ability to steer the vehicle around all relevant vehicle and air-path related axes with the help of control devices. For RV-W's these are aerodynamic control surfaces and usually, in addition, reaction control systems (RCS) in the form of small rocket thrusters located appropriately around the vehicle, for RV-NW's they are in general solely reaction control systems.[1] We stress the fact that only a "trimmed" trajectory is a viable trajectory. For airbreathing (CAV) flight vehicles the influence of the thrust vector of the propulsion system in the lift-drag plane on the longitudinal force and the moment balance must be taken into account.

Trajectory design and optimization must allow for uncertainties in the describing data of the vehicle, its sub-systems, and the flight environment, for a RV-W see, for instance [1]. The uncertainties concern the aerodynamic model—the aerodynamic data set—of the vehicle including uncertainties in the performance data of the control devices, and also uncertainties in the performance data of the propulsion system in the case of CAV's. Uncertainties of other kinds are present as a rule regarding the vehicle mass, the location of the center-of-gravity of the flight vehicle and its moments of inertia. This holds especially for RV-NW's with ablation cooling. With CAV's all these are anyway not constant because of the fuel consumption during flight, and, in the case of TSTO-systems, also because of the separation of the upper stage.

Other uncertainties come in from the sensor systems (air data, acceleration data) etc., and are also given in the form of deviations from the, for the trajectory design chosen, standard atmosphere during the actual mission, especially regarding the density ρ_∞, and the possible presence of wind. The latter concerns in particular CAV's, because these fly predominantly in the troposphere and the stratosphere, Appendix B.

In the following sections we look at the trajectory design and optimization elements which have close connections to aerothermodynamics (guidance objectives, trajectory control variables, systems and operational constraints). We consider the forces acting on a vehicle, discuss the equilibrium glide trajectory of RV-W's and RV-NW's (the compact and frame-consistent derivation of the general equations for planetary flight is given at the end of the chapter), give qualitative results, and show in case studies some examples of trajectories. We refrain from discussing guidance laws, and refer the reader the reader instead to, e.g., [2]. We begin with RV-W's and RV-NW's, where considerable flight experience is available,[2] and proceed with CAV's, where, however, flight experience is not available.

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1 The major role, however, of the RCS of a flight vehicle leaving the atmosphere (above $H \approx 80$ to 100 km) and/or performing orbital flight, is to carry out orbital manoeuvering.

2 The reader is especially referred to [1] about the Space Shuttle Orbiter's reentry guidance.

2.1 Flight Trajectories of Winged and Non-Winged Re-Entry Vehicles

2.1.1 General Aspects

RV-W's and RV-NW's have in common that their re-entry flight as decelerating flight is actually a braking mission. Their large initial total air-path energy

$$E_{t,i} = m\left(gH_i + \frac{1}{2}v_i^2\right), \tag{2.1}$$

is dissipated exclusively by means of the aerodynamic drag. In eq. (2.1) m is the vehicle mass, g the gravitational acceleration as function of the altitude, Section C.1, H_i the initial altitude, and v_i the initial speed.

The dissipation of the large initial total energy requires specific systems constraints of which the dynamic pressure, the thermal surface loads and the aerodynamic load factor belong to the most important ones. The result is an usually very narrow re-entry flight corridor. We show in Fig. 2.1 as an example the flight corridor of the Space Shuttle Orbiter for the operational angle of attack profile [1].

The minimum weight of the Space Shuttle Orbiter's thermal protection system (TPS) is achieved by flying on a large part of the trajectory the maximum angle of attack, consistent with the cross-range requirements, in order to minimize the thermal loads. During the initial five flights, which

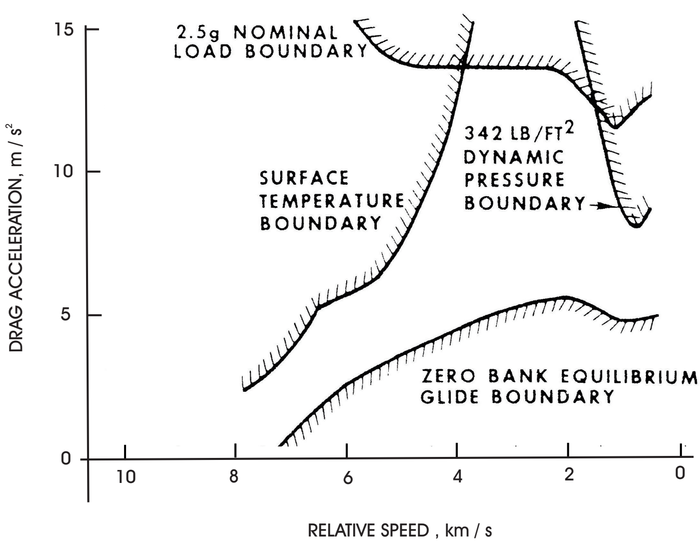

Fig. 2.1. Flight corridor of the Space Shuttle Orbiter (operational flights) [1].

served as test flights, this angle was $\alpha = \alpha_{max} = 40°$, during the following operational flights $\alpha = \alpha_{max} = 38°$ [1].

A RV-W flies, with basically fixed configuration, in a large Mach number and altitude range. During the high speed re-entry it flies at large, and at low Mach numbers at small angles of attack. With increasing angle of attack the effective longitudinal "nose" radius in the stagnation point region of the vehicle increases (rise of effective bluntness).[3] With increasing nose radius, at constant flight speed and altitude, the boundary layer thickness increases and the thermal loads, both the heat flux in the gas at the wall, q_{gw}, and the surface temperature T_w (which without slip-flow effects is equal to the temperature in the gas at the wall T_{gw}, Section 9.1) of the radiation cooled TPS surface, decrease [5].

Increased effective bluntness also increases the portions of the bow shock with large inclination against the free-stream, and hence the wave drag and with that the deceleration[4] of the vehicle along the flight path. The blunt vehicle shape at large angle of attack thus serves both low thermal loads and high drag (and deceleration) [5].

The flight trajectories of RV-W's and RV-NW's can be distinguished in the altitude-velocity map, Fig. 2.2. The lift parameter $\alpha_W = W/(A_{ref}C_L)$ and the ballistic parameter $\beta_W = W/(A_{ref}C_D)$ are derived in Sub-Section 2.1.4. They can be related to each other by the lift-to-drag ratio L/D. The "lifting" re-entry trajectory of RV-W's is much "higher" than that of RV-NW's. Our intuition tells us that the higher the trajectory, the smaller the thermal loads, but the lower the effectiveness of aerodynamic stabilization, trim, and control surfaces. The ballistic or semi-ballistic re-entry of RV-NW's thus is marked by much larger thermal loads than the lifting re-entry of RV-W's.

Cross-range capabilities of RV-W's and especially RV-NW's are limited because of their small lift-to-drag ratios. Usually RV-W's have in the high speed domain a $L/D = O(1)$ due to the blunt vehicle shape and the large angles of attack. The Space Shuttle Orbiter has a trimmed $L/D \approx 1$ at $\alpha \approx 40°$, Fig. 2.3[5] [7]. For the upper stage HORUS of the TSTO reference concept SÄNGER of the former German Hypersonics Technology Programme, [8], $L/D \approx 1.9$ was envisaged at that angle of attack. For RV-NW's we find $L/D = 0.1$ to 0.3 [9], which is achieved by an offset of the center-of-gravity from the centerline, and hence is the trimmed L/D. For purely ballistic re-entry

[3] For the Space Shuttle Orbiter's equivalent axisymmetric body, [3], the "nose" radius rises almost linearly from $R_N = 0.493$ m at $\alpha = 21.8°$ to $R_N = 1.368$ m at $\alpha = 42.75°$ [4].

[4] In trajectory design and optimization the term "drag acceleration" is used instead of the term "deceleration", Sub-Section 2.1.4.

[5] The agreement between the flown L/D data of the trimmed vehicle and the predicted data is very good. The flight data show Mach number independence, Section 3.6.

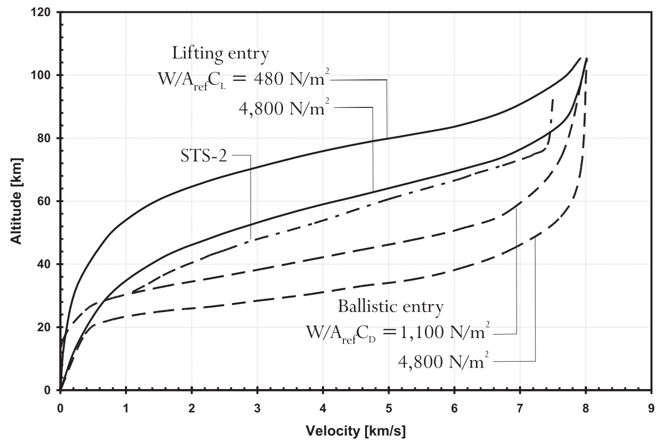

Fig. 2.2. Trajectories of RV-W's and RV-NW's with typical values of lift parameters and ballistic parameters in the altitude-velocity map (STS-2: second flight of the Space Shuttle Orbiter, data from [6]).

capsules $L/D = 0$. All these vehicles can be considered as compressibility or pressure effects dominated flight vehicles, Section 1.1.

Lift-to-drag ratios of O(1) of RV-W's are due to the blunt, although elongated shape of the vehicles—usually with large portions of the lower side being approximately flat, Sub-Section 3.2.2—in combination with large angles of attack.

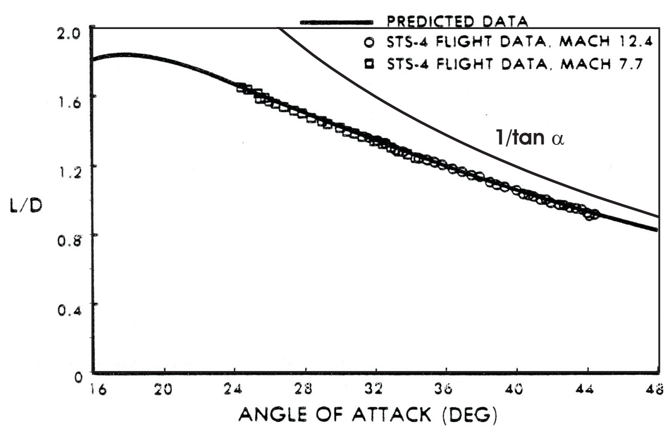

Fig. 2.3. Trimmed lift-to-drag ratio L/D of the Space Shuttle Orbiter in the hypersonic domain as function of the angle of attack α [7]. The large angle of attack interval of the flight data was achieved by transient pushover-pull-up maneuvers around the actual flight angle of attack.

During a re-entry flight, which is performed at large angles of attack, L/D can be increased by both reducing the angle of attack α (reduction of the "effective" bluntness of the configuration) and the actual nose bluntness (nose radius R_N). If we approximate the lower side of a RV-W by an equivalent flat plate, the RV-W-type RHPM-flyer, Section 10.1, and apply Newton's theory, we find for the lift-to-drag ratio $L/D = 1/tan\,\alpha$, which in the case of the Space Shuttle Orbiter is a fair approximation for $\alpha \gtrapprox 25°$, Fig. 2.3. Thus reducing the angle of attack, also for realistic vehicle shapes, is an effective means to increase the lift-to-drag ratio, as is amply demonstrated by Fig. 2.3.

We note, however, that in reality a reduction of L/D of a given flight vehicle is undertaken on appreciable parts of the trajectory via a reduction of L. With the bank angle μ_a of the vehicle an effective lift $L_{eff} \leqq L$ and/or a side force is achieved, which serve as trajectory-control means, Sub-Section 2.1.2.

2.1.2 Guidance Objectives, Trajectory Control Variables, and Systems and Operational Constraints

We discuss now some issues of the above mentioned guidance objectives, trajectory control variables, and systems and operational constraints.

Guidance Objectives: For RV-W's and RV-NW's the most important guidance objectives are:

- **Minimization** of the **time-integrated heat flux** in the gas at the wall $\overline{q}_{gw}$ at selected reference locations

$$\overline{q}_{gw} = \int_{t_0}^{t_{flight}} q_{gw} dt, \tag{2.2}$$

  which is used as a measure of the thickness and hence the weight of the heat protecting or insulating structure. The reference locations are at least the nose cap, approximated by a sphere, where q_{gw} would be the forward stagnation point heat flux, and usually parts of the TPS, where the heat fluxes q_{gw} can be approximated by those of a flat plate or a swept cylinder etc. (see, e.g., [10]). Simple relations for the estimation of q_{gw} are provided in Chapter 10.

  The use of the time integral of q_{gw} in trajectory design and optimization has historical roots. In reality, it is the time integral of q_w, the heat flux which actually enters the TPS or the hot primary structure, which is of importance. In presence of radiation cooled surfaces, Section 9.1, which are the rule for hypersonic vehicles in the velocity and altitude range considered in this book, this heat flux is $q_w = q_{gw}$ - q_{rad}, where q_{rad} is the radiation cooling heat flux q_{rad}.
- **Cross range** achievement. The cross range is the lateral distance of the prescribed landing site from the exit orbital plane. Both the down range—in direction of the trace of the exit orbit plane—and the cross range are