INTERDISCIPLINARY DESIGN OF MODERN HYPERSONIC WAVERIDERS USING THE INTEGRATED PROGRAM PRADO-HY

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ABSTRACT

The objective of this paper is the evaluation of modern hypersonic waveriders obtained from the osculating cone method. Therefore, the design program system PrADO-Hy (Preliminary Aircraft Design and Optimization - Hypersonic), developed by the Institute for Aircraft Design and Structural Mechanics (IFL), was used to simulate the design process with the interactions between the different aeronautical disciplines. The investigations are focussed on the design of a TSTO vehicle, performing a cruise flight from Europe to the equator with an orbiter transferring a payload of 3.3 t to low earth orbit (LEO). Computational results show the convergence of the design process and illustrate the sensitivies of the vehicle if design parameters of the waverider (aspect ratio, design Mach number, etc) are changed. A comparison of a waverider with other nominal concepts for the lower stage of a TSTO vehicle points out that the aerodynamic superiority of the waverider overcomes weight and volume penalities. The results indicate that it should be possible to design a TSTO vehicle using a waverider as a first stage. This configuration would have four engines and a take-off weight of about 300 t, i. e. it is 15.5% lighter than the best conventional solution.

INTRODUCTION

Investigations on hypersonic vehicles, used either for more economic space transportation systems with an airbreathing part or for long-distance cruise flights with internal payload, point out the demand for configurations having a high lift over drag ratio. Renaissance in hypersonic waverider research during the last years led to new shapes (see Fig. 1) offering high aerodynamic efficiency as well as a suitable volume distribution for the integration of fuel tanks, cockpit, payload, etc. Furthermore, the waverider design tools developed allow a flexible vehicle design and provide reasonable accurate aerodynamic predictions even for the off-design behavior. Most of these waverider studies are aimed at the maximization of aerodynamic performance of hypersonic waveriders, however nearly no attempts have been made to optimize other vehicle characteristics at the same time in order to achieve the best shape for a given mission.

To fill this gap, the Institute for Aircraft Design and Structural Mechanics cooperates with the DLR, Institute of Design Aerodynamics. The IFL investigates the mission performance including the determination of fuel mass, engine size, thermal protection system, undercarriage weight, etc. using the integrated computer program PrADO-Hy(1,2), while the DLR creates generic waverider shapes (see Fig. 1a,b) and estimates the aerodynamic data with their waverider program(3). Parametric studies are carried out by the IFL on groups of waverider shapes having common basic design parameters (e.g. aspect ratio, planform, shock angle, etc.) to evaluate the influence of the engine position, fuel volume, undercarriage position, etc. on size and take-off weight of the waveriders. By using these results it is possible to improve the waverider design optimizing the overall mission performance instead of only optimizing the aerodynamic efficiency. At present, the task concentrates on the design of a TSTO concept with a fixed flight path including a 2700 km cruise flight with an orbiter capable of carrying a payload of 3.3 t into LEO (see Fig. 2).

WAVERIDER: PRINCIPLE AND AERODYNAMIC DESIGN

This chapter provides only a short overview, sufficient enough to serve as the basic knowledge for the design engineer´s task.

The basic idea in the generation of hypersonic waveriders is the inversion of the normal design process. Instead of having a certain configuration and estimating its surrounding flowfield (as well as its aerodynamic data) there is a given shock surface which is contained within the limits of the lower planform of the body. This vehicle, riding on the shock surface, hence called waverider, efficiently uses the high post shock pressure to provide the majority of the vehicle´s lift.

Therefore, the generation of a waverider for inviscid flow can be subdivided into three steps:

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a) Choose a known shock surface given by one well defined flowfield or a composition of flow fields
b) Define an upper (freestream) surface whose intersection with the shock surface forms the leading edge of the vehicle
c) Follow the streamlines passing through the leading edge to get a streamsurface that can be replaced by a solid surface for inviscid flow. This solid surface forms the underside of the waverider.

If an oblique shock is used, created by a wedge and a "roof-type" upper surface, one will get the class of caret-wings created by Nonweiler(4) (see Fig. 3). Unfortunately they are not suitable for hypersonic cruise vehicles because the large wetted surface area creates too much friction drag and the configuration provides too little volume for the integration of. fuel tanks, engines, undercarriages, etc. To overcome these insufficiences, Bowcut et al. introduced the class of viscous optimized waveriders(5) (see Fig. 3), generated by one conical flowfield described by the Taylor-Maccol ordinary differential equation. These waveriders show high lift over drag although skin friction is included, an acceptable volumetric efficiency and less camber, so that the cross sections are suitable for the integration of tanks.

To achieve a higher flexibility, Center and Sobieczky developed the osculating cones concept(3). Instead of using only one conical shock, osculating cones waveriders are generated by specifying a completely arbitrary shock shape at the configuration´s exit plane and treating each region along the span as one of a local conical flow. If only one constant shock angle is used and the curvature of all cones, which are lying on the shock profile (which is the intersection between exit plane and shocksurface) exactly match this profile at the point of tangency, then the vertex of each osculating cone will be known. After the upper surface is chosen the leading edge and the underside of the waverider can be calculated. This method led to the WIPAR program for the interactive design of waveriders(3).

The Institute of Design Aerodynamics of the DLR applies this program to the generation of waverider shapes which are further investigated by the IFL. While WIPAR only predicts the aerodynamic data at the design point other methods must be used to calculate the off-design aerodynamics. Therefore, the program SOSE(6) based on a modified shock expansion method is used as a fast and reasonable accurate tool as well as the DLR Euler code CEVCATS(7).

CONCEPT AND STRUCTURE OF THE PROGRAM PrADO-Hy

Extensive computational capabilities have been developed to analyze hypersonic aircraft. The problem in the design of such hypersonic configurations is that there are - compared to normal aircraft - many more technological unknowns, little statistical data for a first design estimation and many high sophisticated non-linear problems which are strongly coupled. Therefore, the necessity exists of having a flexible computerized analysis and synthesis tool to simulate the interactions between the various disciplines involved in the design process (e.g. aerodynamics, flight mechanics, weight estimation, etc.). Furthermore, it must have the capability of growing and becoming more accurate with increasing knowledge.

The main objectives of such a program are:
- Proof of convergence (checking the feasibility of different configurations)
- Sensitivity investigations to obtain the influence of certain design parameters, new technologies, materials, etc. on the complete system "aircraft"
- Evaluation of different concepts fulfilling fixed requirements (e.g. mission, payload, etc.)
- Optimization of configurations under consideration of a merit function (e.g. minimization of fuel consumption, DOC, MTOW, etc.)
- Definition of new technological goals in order to reach the given design target

Derived from these tasks the following general requirements for a computerbased design tool result:
- Flexibility (program must be adaptable to new design tasks)
- Modularity (implemention of new design modules)
- Simple embedding of program modules developed by other disciplines/institutions
- Necessity of well arranged interfaces
- Possibility of linking data bases (e.g. material data, engine characteristics, etc.)
- Implementation of a data management system for an open-ended system

Considering the requirements described and with the background knowledge of the design of civil transport aircrafts, the Institute for Aircraft Design and Structural Mechanics started a research project to develop the computer-augmented preliminary design program PrADO-Hy for the evaluation of hypersonic aircraft configurations(2) in 1990. Corresponding to the different tasks appearing during the design of a hypersonic aircraft, the program can be devided into four levels (see Fig. 4):

1.Level: Data Input/Output.
These routines are necessary for the data input of the user-specified baseline design (e.g. mission requirements and constraints, evaluation of important design parameters such as weight, etc.). They build up a complete data base for the configuration. Missing values are completed by estimations from a statistical data processor. Fixed

external data bases including e.g. material properties, engine performance characteristics, etc. are available. The possibility of storing the complete internal data base provides access to the results for later calculations like off-design performance, graphical result evaluation or a detailed FE-based structural analysis.

2. Level: Optimization Loop. Herein routines are included for the minimization of a given objective function (e.g. take-off-weight, fuel consumption, costs, etc.) varying chosen design parameters (e.g. cruise speed and altitude, etc.). For the optimization different methods are available(1). Other programs within this level generate the design-specific merit function, check the design constraints and save the new set of design parameters.

3. Level: Multidisciplinary Design Process. This level simulates the sequential interdisciplinary design process. For the exchange of input and output data between the main modules a data management system is used which stores all actual data during the iteration in the internal data base. With this kind of data handling the order of the modules in the design process can easily be rearranged or they can work as "stand-alones" combined in a user specified manner as a "design tool-kit".

4. Level: Design Program Libraries. The program libraries include the different physical models used during the design process. They form the kernel in which methods developed by different disciplines can be integrated as new modules to enhance performance and accuracy of the design code.

Design Synthesis

The design synthesis placed in the 3. level of PrADO-Hy simulates the sequential iterative process of aircraft design including the large number of interdependencies between the various disciplines (e.g. aerodynamics, flight mechanics, structure mechanics, etc.) involved. A convergent design with a consistent internal data base results from the process. This can be used for the calculation of a merit function necessary for the optimization in the second level. After the optimization variables are changed, the iterative phase will restart. This loop will be repeated until an optimum of the merit function is reached.

The first step during the iteration (see Fig. 5) is the data input. Therefore a complete but not necessarily consistent data base must be submitted including design and mission requirements as well as a list of optimization variables.

The iteration starts with the geometric sizing of the vehicle. The subsequent performance analysis estimates the fuel mass and the engine thrust of the vehicle. Therefore, aerodynamic data, engine performance and fuel consumption have to be provided. After the engine sizing module, calculating the take-off thrust and the number of engines, two inner loops control the convergence of thrust and fuel volume. If convergence is not achieved, there will be a feedback with adapted values for fuel mass and/or engine thrust. Otherwise, the iteration proceeds with the weight estimation of the vehicle.

For the first stage the weight for TPS, structure, engines, tanks, etc. is calculated in seperate modules using a combination of analytical methods and programs based on statistics. The sizing of the upper stage is optional and represents a small design program with only one inner loop controlling the launch weight convergence. The next convergence test concerns the take-off weight. If it does not converge, the iteration will be repeated with a modified take-off weight.

The last step during the design synthesis represents the tailplane design, where stability and control aspects are considered and compared with assumed values. Non-tolerable differences require a change of the tailplane areas and a complete new iteration with modified values.

Please refer to ref. 1,8 and 9 for a more detailed description of the physical models used within the multidisciplinary design process.

DESIGN STUDY OF A TSTO CONCEPT

Design requirements

For the investigation of the TSTO vehicle, one nominal mission was selected. A hypersonic lower stage will transport an orbiter from Europe to the staging point near to the equator and then it will return. After separation the orbiter will transport the payload into an elliptic orbit.

At the end of this article - in order to estimate the potential of the waverider - a comparison is made with other nominal configurations. All of them are used as the lower stage of a TSTO vehicle and are designed to fulfill the requirements of the following given mission:

orbiter payload: 3.3 t (incl. 3 astronauts)
orbit at the end of upper stage ascent:
inclination: 28^0
apogee: 463 km
perigee: 70 km
staging conditions:
altitude: 32.4 km
Mach number: 6.3
upper stage flight
path angle at separation: 6^0

The flight path of the lower stage (see Fig. 2) is identical for all configurations. Although the optimization of the flight trajectory is necessary in order to use the full capabilities of a certain configuration, a fixed flight path reduces the number of design variables and simplifies the comparison of the different concepts. The flight path consists of five segments:

- An ascent with the changeover from turbine to ramjet engines at about Ma = 3 .
- The cruise flight above the ozone layer at Ma = 4.5 and an altitude of 26 km.
- A second climb and acceleration phase.
- A pull-up maneuver to obtain the staging conditions as initial conditions of the second stage.
- A cruise flight during the return of the first stage at a higher altitude due to the lower weight after staging.

Basic configuration

As previously mentioned we startet with a given flight path including a cruise flight at Mach 4.5. Unfortunately the aerodynamic design of the waverider´s shape created for this Mach-number (see Fig. 1a) has a great camber in spanwise direction leading to difficulties for the integration of tanks, cockpit, landing gear, etc. One way to reduce this camber is a higher aerodynamic design Mach-number. This is only possible if there is a good off-design performance. Aerodynamic investigations for the hypersonic flow regime(10) as well as requirements for an acceptable sub- and transsonic performance and considerations about the integration of components (e.g. tanks, propulsion group, landing gear, etc.) led finally to a waverider with a design Mach-number of 12.0 and an aspect ratio of 1.33 (see Fig. 1b). Although the refinement of the physical models incorporated in the program system PrADO-Hy reduced the performance of this waverider it was kept as the basic configuration. Fig. 1c illustrates the impact of the geometric requirements on the shape of the waverider. Espcially the penetration of the propulsion group into the body and the flattening out at the rear of the body cause a loss of usable volume and a higher structure weight due to the reduced thickness of the body. The data and cutaway drawings in Fig. 6 illustrate the complete baseline design.

There are some remarks necessary which are valid for all configurations discussed in this paper. The available data concerning the engine performance are similar to the engine model used within the German "Sänger" project(11). A scaling of the engine is not possible. Because of the fixed engine geometry only the number of engines could be changed. For the careful integration of the engines into the configuration it is evident to incorporate an aerodynamic bookkeeping method and to provide the correct flow conditions at the inlet of this engine. This results in an angle of 9.2° between the underside of the forebody responsible for the precompression of the airflow and the reference axis of the engine. Requirements for the load distribution between nose and main gear, the retraction of the landing gear, the tire selection and the take-off performance are considered for the position and size of the landing gear .

The upper stage design depends on the staging conditions, the orbit at the end of the ascent and the orbiter payload. All these requirements are mission depending. Due to the fixed mission for the accomplished investigations all configurations have a common upper stage. The PrADO-Hy module for the upper stage sizing was used to design the orbiter. The determined data for the orbiter are a take-off weight of 108.4 t, a length of 31.2 m and a wing span of 15.8 m. The relative position of the orbiter on the lower stage is fixed by the requirement that at the staging point the centers of gravity of the lower stage and the orbiter have the same position in longitudinal direction. This is necessary to avoid a sudden change in the center of gravity of the first stage after the separation of the orbiter.

The influence of the design Mach-number

In this chapter the influence of the design Mach-number on the size and the performance of a TSTO vehicle designed to fulfill the given mission (see Fig. 7) will be discussed. As mentioned before this sensitivity study led to the choice of the basic configuration.

From the aerodynamic design two characteristic results are available:

- The (ideal) maximum L/D_{MAX} for the waverider without upper stage during hypersonic flight
- The volumetric efficiency $V^{2/3}/S$

Both are first indicators for the overall performance of a certain configuration. Fig. 7 shows a decrease of the maximum L/D_{MAX} for the first waverider ($Ma_D = 4.5$) compared to those with a higher design Mach-number. This is only possible because these waveriders demonstrate a good off-design performance(10). The volumetric efficiency has a maximum for the basic configuration. Much more interesting is the following chain of cause and effect:

The great camber in spanwise direction (see Fig. 1a) makes it difficult to integrate the tanks having an elliptical cross section in the given shape of the waverider with $Ma_D = 4.5$. The sizing of the aircraft leads to an increase of the reference area S which is relatively higher compared to the increase of the take-off weight (MTOW). A large portion of this weight is the fixed orbiter mass. The result is a lower wing-loading and lower aerodynamic performance during the mission when the L/D_{REAL} depends on the required lift coefficient. All these couplings between geometry, weight, necessary thrust, etc. occur during the design iteration and result in an exponential increase of thrust (T_{TL}) and take-off weight.

For the waverider with a design Mach-number of 20.0 these effects lead into the opposite direction but the changes are smaller. Although the volumetric efficiency declines, the smaller camber in spanwise direction simplifies the volumetric integration of elliptical tanks leading to a higher wing loading. The L/D_{REAL} during cruise flight at Ma = 4.5 with the orbiter is even a little bit higher compared to the basic design. Therefore, the result of the integrated design process is a lighter aircraft with high cruise performance. This effect was found recently using the refined version of PrADO-Hy and was not seen in previous studies(9).

From the designers point of view this study can be summarized in the following statements:

- The volumetric efficiency is not sufficient as the sole indicator for the usable volume for the component integration.
- The wing loading appears to be one of the important design drivers for hypersonic waveriders.

The influence of the aspect ratio

In order to find out more about the influence of the aspect ratio on the design of hypersonic waveriders a sensitivity study was carried out with aspect ratios from 0.81 to 1.83 (see Fig. 8).

The maximum possible L/D_{MAX} during hypersonic flight is nearly the same for all configurations whereas the volumetric efficiency becomes smaller with higher aspect ratios. This is caused by the fact that all waveriders in this study have the same ratio of thickness at the rear of the body to body length(10) , i.e. the relative thickness in spanwise direction decreases. In combination with the assumption to use tanks having an elliptical cross section with a limited ratio of major to minor axis and the use of low-density liquid hydrogen as fuel the usable volume for higher aspect ratios decreases rapidly. A consequence of this is an increasing size and reference area of such a configuration. In contrast to this progressive behavior the operational empty weight (OEW) grows moderately. A detailed analysis of the obtained design data shows that the waverider with an aspect ratio of 1.83 has structural weight of 119.4 t (41.8% OEW) without vertical stabilizer whereas the waverider with the lowest aspect ratio of 0.81 has a structure weight of 44.0 t (31.8 % OEW). The ratio of structure weight to reference area decreases from 33.2 kg/m^2 to 26.4 kg/m^2 indicating the influence of the bending moments in spanwise direction on the stresses in the structure. But this effect is overcompensated by the higher utilization of the available volume due to the better integration of the fuel tanks. The resulting higher wing loading allows a cruise flight with the upper stage at a higher lift coefficient which lies near to that required for the optimum aerodynamic performance of the configuration with the lowest aspect ratio. During the cruise flight the waveriders with the higher aspect ratios need a lower lift coefficient and do not reach their optimum L/D.

The computational results point out the significant impact of the wing loading on the performance of the waverider. Referring to Fig. 8 the waverider with the lowest aspect ratio would be the best solution if the take-off weight was used as the merit function. But it should be taken into account that the sub-/transsonic behavior of waveriders with small aspect ratios still has to be investigated and that the extrordinary length of the vehicle may cause problems for the landing gear design and problems during taxying.

The influence of the body angle α

One possibilty to overcome the penalties introduced by the penetration of the propulsion group into the body and the flattening out of the rear is to enlarge the thickness in the midplane of the body. The body angle α is the measure of the ratio of thickness to body length (see Fig. 6). The positive effect of a higher body angle α is an increasing volumetric efficiency whereas the maximum L/D_{MAX} decreases (see Fig. 9). The L/D_{REAL} which is important for the sizing of the vehicles and depends on the required lift coefficient during the mission remains nearly constant within the chosen range of the body angle α. Once again the increasing wing loading is responsible for this effect caused by a higher utilization of the available volume due to the better integration of the volumious elliptic tanks for liquid hydrogen.

A closer look at the decreasing operational empty weight shows that beside the trivial effect that smaller aircrafts have a lower weight the reduced engine number has an important impact on this reduction. The contribition of the structure weight without vertical stabilizer to the operating empty weight decreases from 40.1 % for a body angle of 4.63° to less than 32 % for a body angle of 6.11°. There are two main reasons that lead to lower stresses in the skin panels and thus to a reduced weight of the structure. The first one is a greater total thickness of the structure. The second one is the smaller area covered by the propulsion group whose penetration into the body has a weakening effect on the structure. The contribution of the other components (landing gear, vertical stabilizer, systems, etc.) to the operating empty weight remains nearly constant for a changing body angle α.

All these effects listed above are included within the numerical models of PrADO-Hy and result in a lighter

TSTO vehicle. While the enlargement of the body angle α from 4.63° to 5.5° offers a drastic improvement of the design the further enlargement to a body angle α of 6.11° shows only a small additional weight reduction. Therefore, the refinement of the shape was concentrated on the waverider with a body angle of $\alpha = 5.5°$. Another reason is the higher drag during sub-/transsonic flight due to the greater thickness of the body.

The variation of the body angle α represents a typical preliminary design task: There exists one parameter driving two characteristic indicators for the suitability of a design into opposite directions. Using the integrated program system PrADO-Hy it was possible to identify the important sensitivities and to improve the design of the waverider.

Concept evaluation

The concept evaluation gives an impression of the suitability of the waverider concept in comparison with other nominal concepts for the lower stage of a TSTO vehicle and demonstrates the flexibilty of PrADO-Hy which was also used for these studies.

In this evaluation four different configurations (see Fig. 10) were sized to fulfill the given mission. The first one is the basic configuration (see Fig. 6) which is used as the reference design. An improved waverider which has a design Mach-number of 12.0, a body angle of 5.5° and a "double-delta" wing planform to achieve a higher wing loading is the second configuration. The lifting-body configuration(12) which has an elliptic cross section and whose aerodynamic data were taken from wind tunnel measurements(13) represents the third concept in this evaluation. For the blended-body a typical shape was chosen and the aerodynamic data were obtained using a handbook method(14).

Fig. 11 shows the results of this evaluation. The bars indicate the relative change of the design parameters compared to the basic waverider configuration whereas the table at the bottom of the figure lists the absolute values of the parameters indicated above.

The comparison between the two waveriders shows the improvement achieved from the higher body angle and the double-delta wing. This leads to a take-off weight of 300 t for the improved design which is 27.1% lower compared with the basic configuration. Especially the lighter structure weight and the smaller number of engines contributes to this reduction. These differences point out the necessity for a careful choice and investigation of the parameters governing the design.

The lifting body configuration has the highest take-off weight of all configurations. The low aerodynamic performance is the design-driver leading to the necessity of six oversized engines and a fuel weight of 145.1 t. The smaller wing area is a benefit of the superior utilization of the available volume and is responsible for the relative small structure weight and operational empty weight.

The take-off weight of the blended-body configuration lies between the two waverider configurations. A part of the lower aerodynamic performance is compensated by the higher utilization of the available volume. The ratio of structure weight to reference area is nearly the same as for the basic waverider configuration "A". The advantages of the waverider "B" in comparison with the blended-body configuration result from a smaller ratio of structure weight to reference area and a better L/D during cruise flight with the upper stage.

In this comparison the improved waverider "B" has the lowest take-off weight which is an indicator for the overall performance of a TSTO vehicle. There is still a remarkable advantage over the blended body configuration. The basic configuration shows that the waverider is not always the best choice for a hypersonic vehicle and that the performance of waverider shapes has to be investigated carefully.

CONCLUSION

The program PrADO-Hy was used as a tool to find the best solution for a given mission and standards of technology. This was demonstrated by sensitivity studies of modern hypersonic waveriders. These studies indicate that the wing loading has much higher influence on the attainment of high aerodynamic efficiency compared to more conventional designs. Taking into account the results from these parametric studies it is possible to find a waverider configuration which can be used as the first stage of a TSTO vehicle capable of bringing a payload of 3.3 t into LEO and having a take-off weight of 300 t. Compared to other hypersonic concepts for the first stage the waverider offers a take-off weight which is 15% lower than the best conventional concept. This points out the great potential of hypersonic waveriders. Therefore, further studies are to be recommended because there are still some important questions to clarify e.g. the behavior during low velocity flight, the leading edge design, etc..

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REFERENCES

[1] Kossira, H.; Bardenhagen A.; Heinze, W.: "Investigations on the Potential of Hypersonic waveriders with the Integrated Aircraft Design Program PrADO-Hy", AIAA-93-5098, Munich 1993

[2] Kossira, H.; Heinze, W.; Bardenhagen, A.: "An Integrated Computer-Program-System for the Preliminary Design of advanced Hypersonic Aircraft (PrADO-Hy)" in "Orbital Transport - Technical; Meterological and Chemical Aspects (Third Aerospace Symposium, Braunschweig 26.-28. August 1991)", Eds. H. Oertel, H. Körner, Springer-Verlag, Germany, 1993

[3] Center, K.B.; Sobieczky, H.; Dougherty, F.C.: "Interactive Design of Waverider Geometries", AIAA-91-1697, 1991

[4] Nonweiler, R.T.F.: "Aerodynamic Problems of Manned Space Vehicles", Journal of the Royal Aeronautical Society, Vol. 63, 1959

[5] Bowcutt, K.B.; Anderson, J.D.; Capriotti, D.: "Numerical Optimization of Conical Flow Waveriders Including Detailed viscous Effects", AGARD CP-428, 1987

[6] Eggers, Th.: "Calculation of Three-Dimensional Bodies in Hypersonic Flow with Surface Inclination Methods", DLR-IB 129-92/2, DLR-SM-EA, 1992

[7] Radespiel, R.; Kroll, N.: "Extension of the Navier-Stokes Code CEVCATS to Hypersonic Equilibrium Flows", DLR-IB 129-92/21, DLR-SM-EA, 1992

[8] Heinze, W.; Kossira, H.; Bardenhagen, A.: "Integriertes Programmsystem für den Konzeptentwurf wiederverwendbarer Raumtransporter", Zeitschrift für Flugwissenschaft und Weltraumforschung 17, 1993

[9] Heinze, W.; Bardenhagen A.;Kossira, H.: "Ein Beitrag zum Gesamtentwurf von Hyperschallfluggeräten auf Basis neuer Wellenreiter-Konfigurationen", DGLR Jahrestagung, Göttingen, 1993, DGLR-paper 93-03-098

[10] Eggers, T.; Sobieczky, H.; Center, K.: "Design of Advanced Waveriders with High Aerodynamic Efficiency", AIAA-93-514; Munich, 1993

[11] Schaber, R. (MTU-EPSB): "SÄNGER Konzeptstudie - Antrieb -, Phase 1b, Antriebsdatensatz 11/92"

[12] Neuwerth, G.; Staufenbiel, R. W.: "Geometrie der Konfiguration ELAC-1", Internal Report of the Sonderforschungsbereich 253, No. 1, RWTH Aachen, 1990

[13] Nelms, W. P.; Thomas, C. L.: "Aerodynamic Characteristics of an All-Body Hypersonic Aircraft Configuration at Mach Numbers from 0.65 to 10.6", NASA TN D-6577, Washington, 1971

[14] Finck, R.D.; Hoak, D.E.:"USAF Stability and Control Data Compendium", McDonnell-Douglas, Revision 1972, Contract FF 33615-71-C-1298

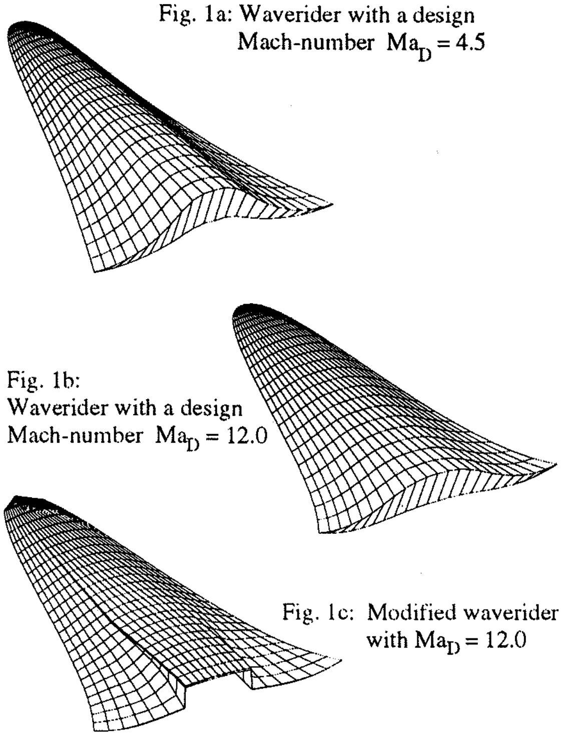


Fig. 1a: Waverider with a design Mach-number $Ma_D = 4.5$

Fig. 1b: Waverider with a design Mach-number $Ma_D = 12.0$

Fig. 1c: Modified waverider with $Ma_D = 12.0$

Fig. 1 Waverider shapes

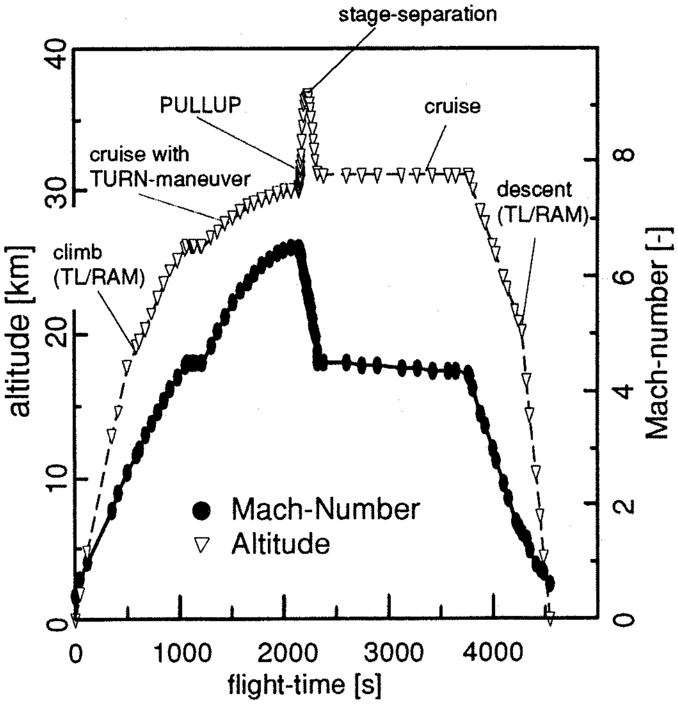
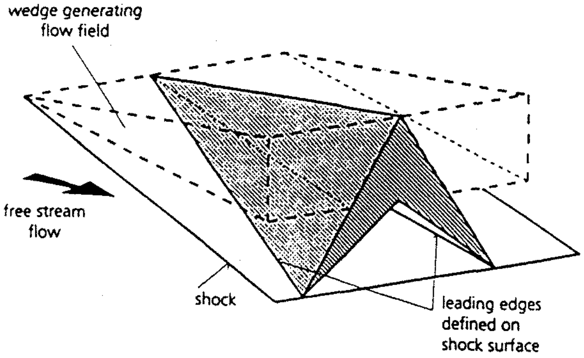
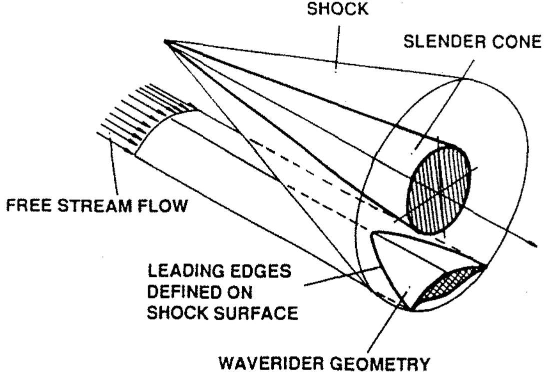


Fig. 2 Flight-path for a TSTO-concept



Caret-Wing waverider (Ref. 1)



Waverider derived from conical flow field (Ref. 5)

Fig. 3 Construction of waveriders from known flowfields

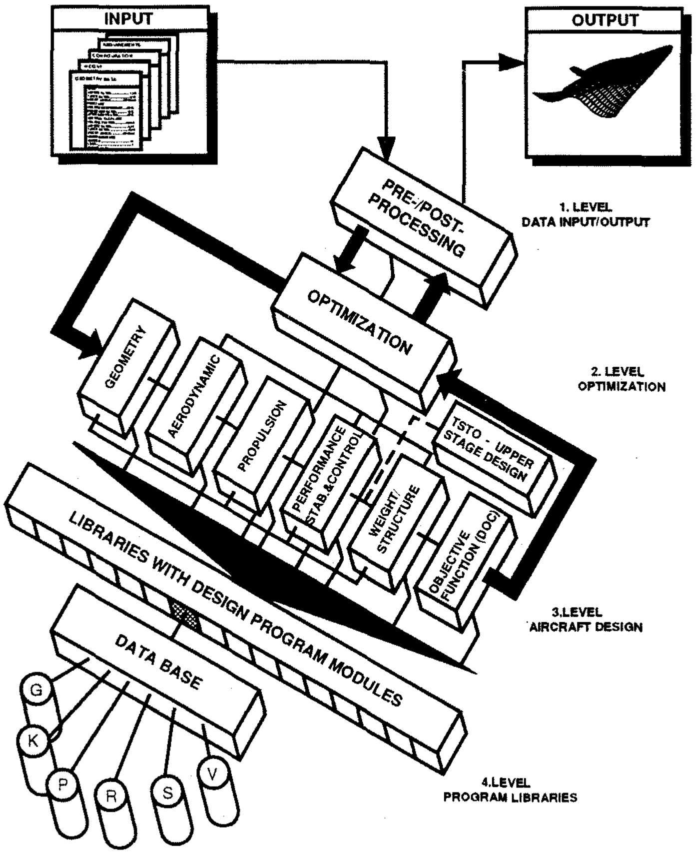


Fig. 4 Structure of the design program PrADO-HY.

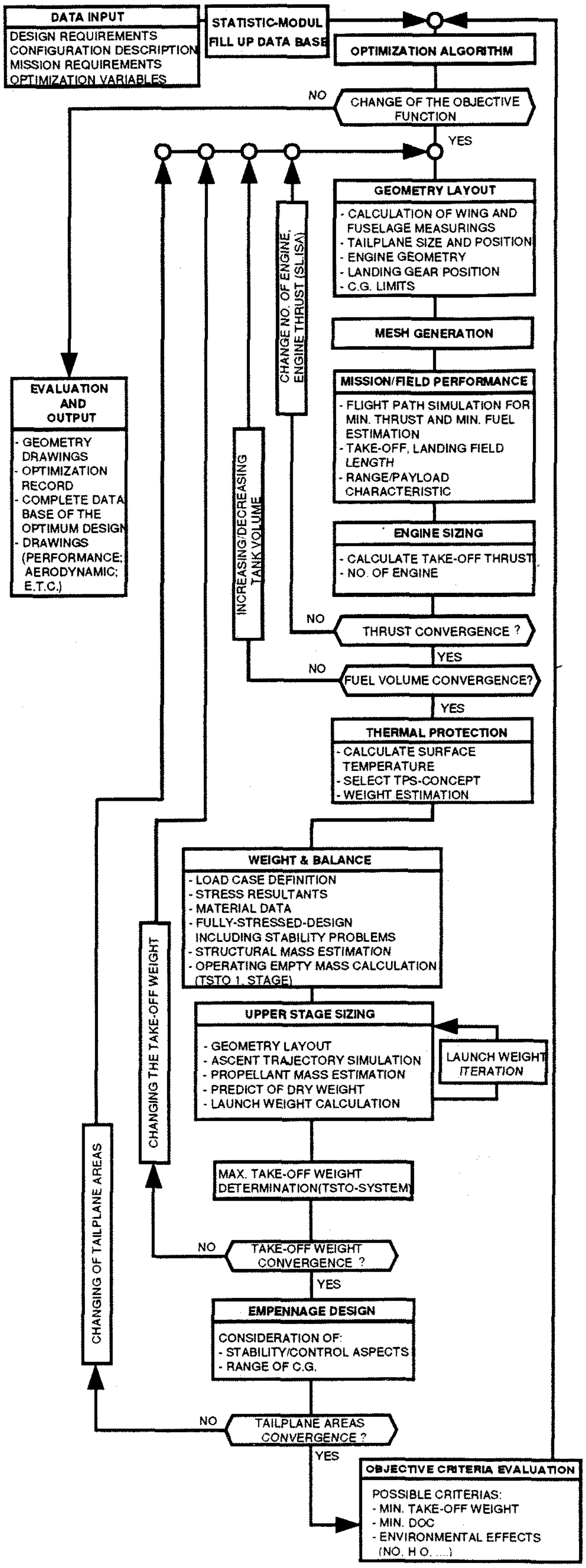
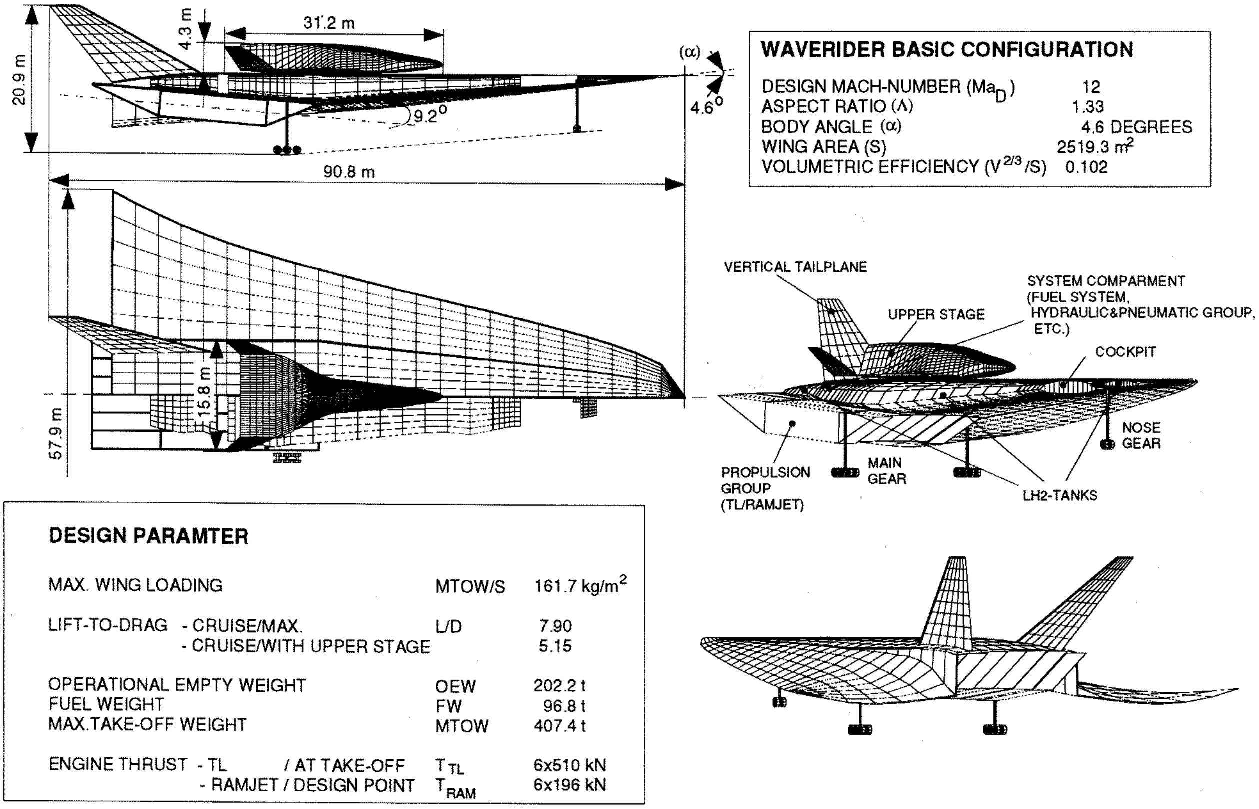


Fig. 5 Flowchart of the design process (3. level).



WAVERIDER BASIC CONFIGURATION

DESIGN MACH-NUMBER (Ma_D)	12
ASPECT RATIO (Λ)	1.33
BODY ANGLE (α)	4.6 DEGREES
WING AREA (S)	2519.3 m^2
VOLUMETRIC EFFICIENCY ($V^{2/3}/S$)	0.102

DESIGN PARAMTER

MAX. WING LOADING	MTOW/S	161.7 kg/m^2
LIFT-TO-DRAG - CRUISE/MAX.	L/D	7.90
- CRUISE/WITH UPPER STAGE		5.15
OPERATIONAL EMPTY WEIGHT	OEW	202.2 t
FUEL WEIGHT	FW	96.8 t
MAX.TAKE-OFF WEIGHT	MTOW	407.4 t
ENGINE THRUST - TL / AT TAKE-OFF	T_{TL}	6x510 kN
- RAMJET / DESIGN POINT	T_{RAM}	6x196 kN

Fig. 6 Basic configuration

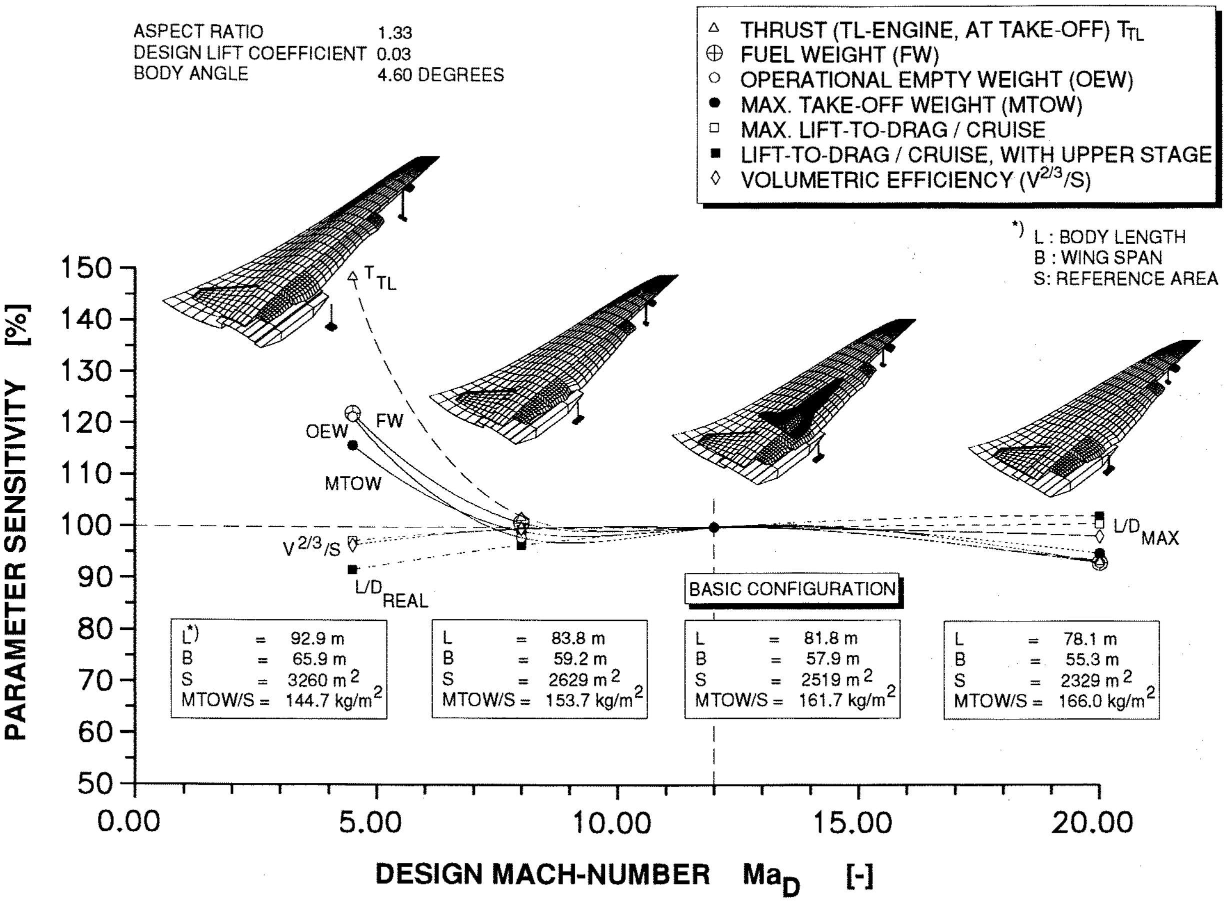


Fig. 7 Influence of the design Mach-Number

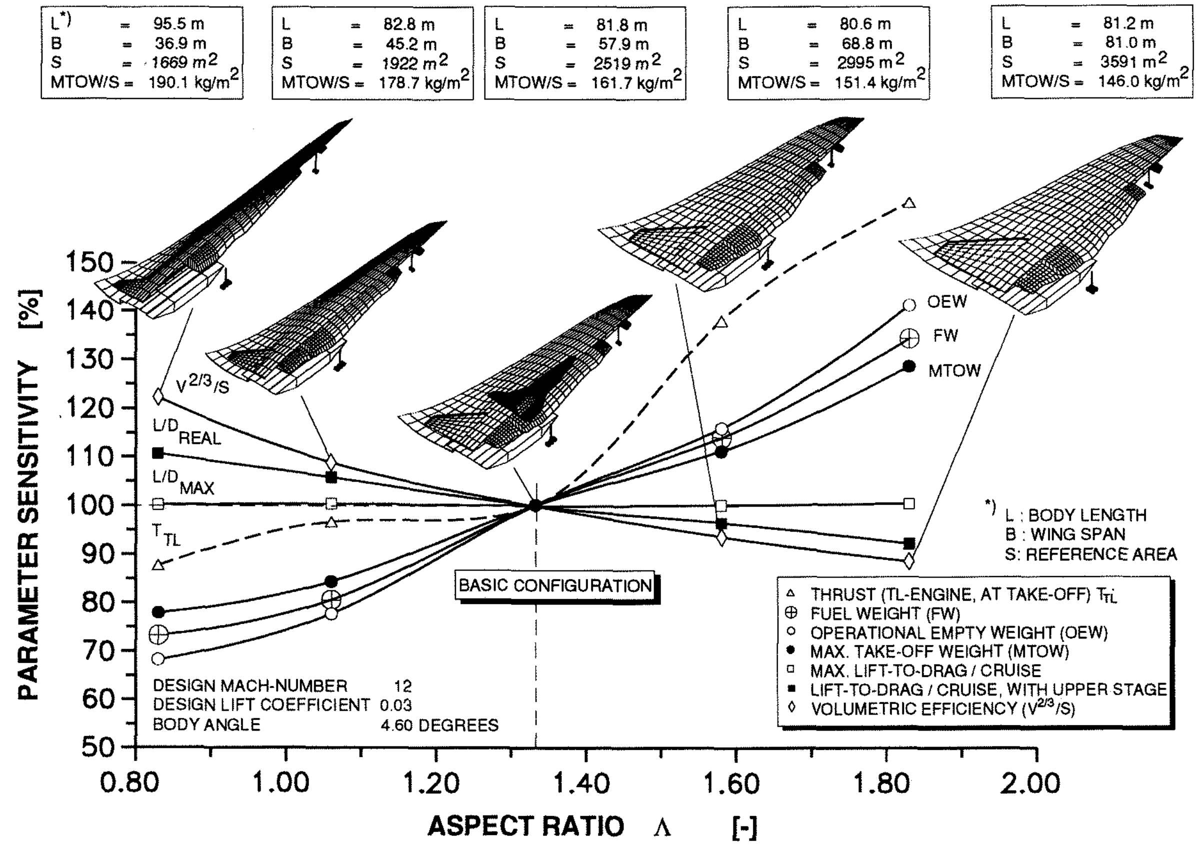


Fig. 8 Influence of the aspect ratio

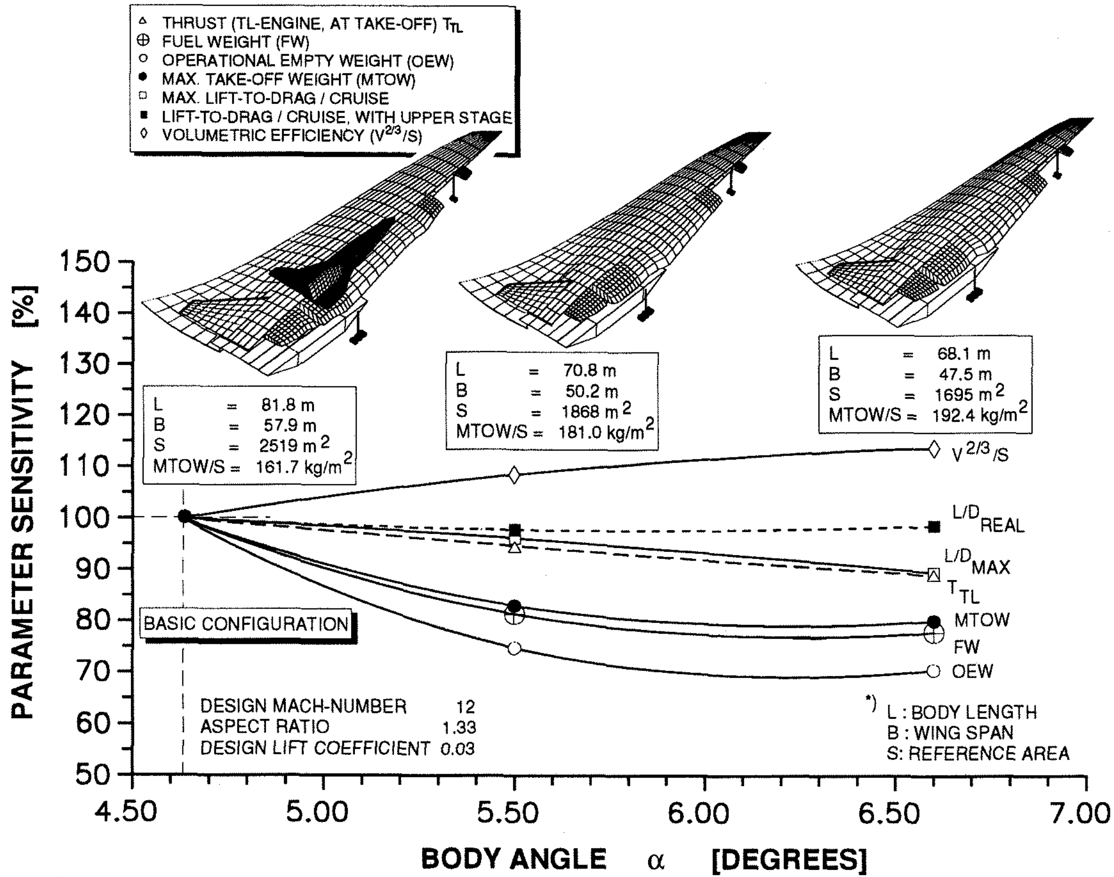


Fig. 9 Influence of the body angle

WAVERIDER WITH DOUBLE-DELTA WING PLANFORM

ASPECT RATIO	1.35
WING AREA	1506 m^2
EGINE THRUST - TL (TAKE-OFF)	4x508 kN
- RAMJET (DESIGN POINT)	4x234 kN
DESIGN MACH-NUMBER	12
BODY ANGLE	5,6 DEGREES

LIFTING-BODY-CONFIGURATION

ASPECT RATIO	0.72
WING AREA	1427 m^2
EGINE THRUST - TL (TAKE-OFF)	6x612 kN
- RAMJET (DESIGN POINT)	6x284 kN

BLENDED-BODY-CONFIGURATION

ASPECT RATIO	1.15
WING AREA	1623 m^2
EGINE THRUST - TL (TAKE-OFF)	5x448 kN
- RAMJET (DESIGN POINT)	5x209 kN

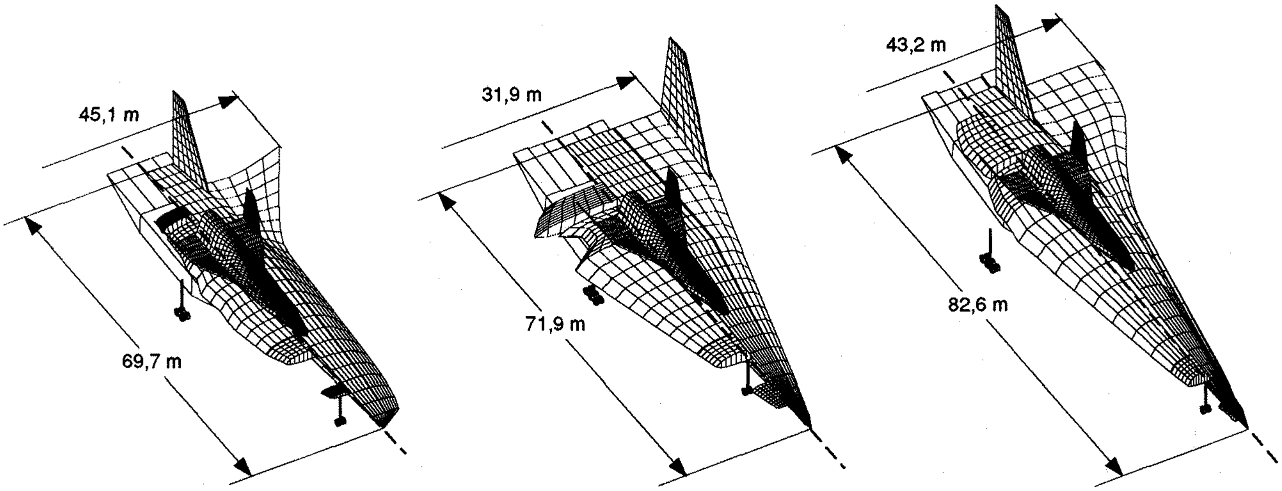
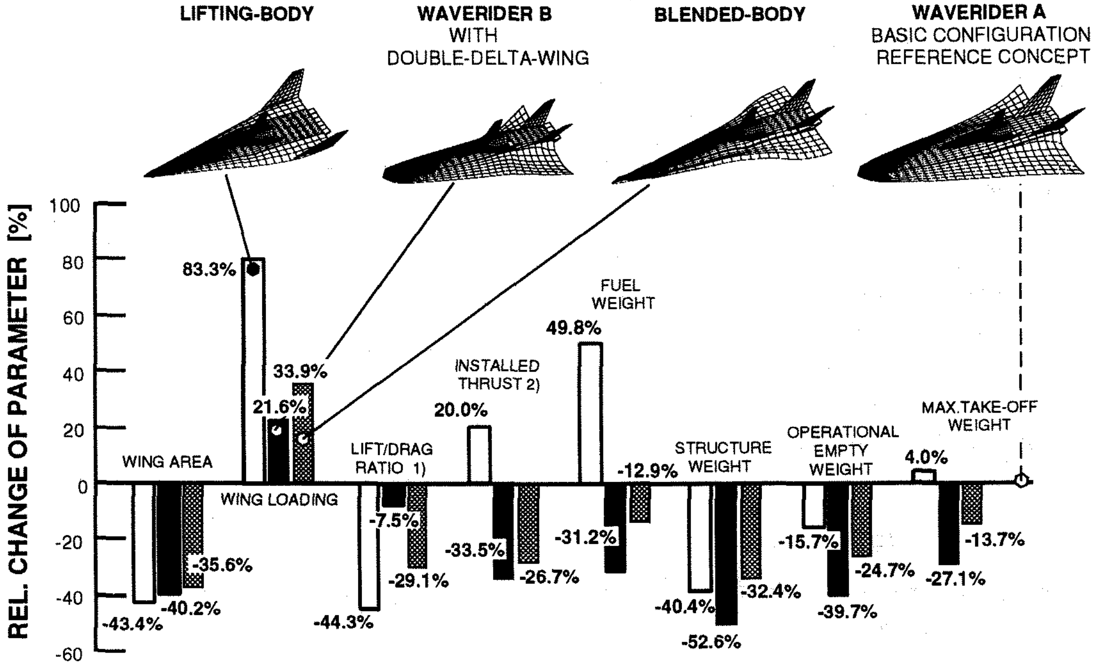


Fig. 10 Nominal configurations for the first stage of a TSTO vehicle



	m^2	kg/m^2	-	kN	t	t	t	t
WAVERIDER A	2519	162	7.9	6x510	96.8	86.1	202.2	407.4
WAVERIDER B	1506	197	7.3	4x508	66.6	40.8	121.9	296.9
BLENDED-BODY	1623	217	5.6	5x448	84.3	58.2	152.1	351.5
LIFTING-BODY	1427	297	4.4	6x612	145.1	51.3	170.3	423.8

1) CRUISE: 26 km, Ma 4.5; WITHOUT UPPER STAGE 2) TL-ENGINE; THRUST AT TAKE-OFF

Fig. 11 Concept evaluation