SIMULATION OF ENGINE/AIRCRAFT DYNAMIC BEHAVIOUR FOR HYPERSONIC FLIGHT VEHICLES

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Abstract:

The steady and dynamic engine/aircraft operating behaviour of a hypersonic flight vehicle is studied using a real-time simulation. The basics of the engine simulation will be presented. The reactions of the aircraft on the dynamics of the propulsion system are shown. Besides nominal flight operation emphasis is laid on engine failure simulation (flame out, intake choking). For the presented reference two-stage-to-orbit concept aircraft controllability aspects are discussed.

Nomenclature

A	Area
F	Force
H	Altitude
M	Mach number
PL	Power lever
T	Temperature
c_f	Thrust coefficient
c_p	Pressure coefficient
$\dot{m}$	Massflow
n_H	Gas generator rotor speed
p	Pressure
q	Dynamic pressure
q	Pitch rate
x,y,z	Cartesian coordinates
Φ	Stoichiometric ratio
Π	Pressure ratio
α	Angle of attack
β	Gross thrust vector angle
γ	Flight path angle
η	Elevator deflection
η	Efficiency

Indices:

AB	Afterburner
g	Gross
p	Pilot input
t	Total
∞	Ambient condition
0	Intake entry condition
1, 2	Intake
2, 3	Compressor section
3, 4	Combustion turboengine
4, 5	Turbine section
6, 7	Reheat
7, 8, 9	Exhaust nozzle system

1. Introduction:

Significant reduction in launch costs is one of the objectives in the development of future space transport systems. Using fully reusable systems is one possible way. Horizontal take-off and landing aircraft meet the main requirements to reuse virtually all system components and simplify considerably the ground operations and flight preparations. [1, 2]

Due to its lower thrust requirements compared to conventional rocket or Single Stage To Orbit (SSTO) systems, the Two-Stage-To-Orbit (TSTO) concept allows the use of a combined-variable-cycle air breathing turbo-ramjet engine with subsonic combustion. High requirements are set on the propulsion system that can only be accomplished by sensibly utilizing parts of the airframe as parts of the propulsion system (e.g.,

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precompression along the forebody of the aircraft, Single Expansion Ramp Nozzle, SERN). This leads to a strong coupling between the two components, making no longer possible to consider separately the propulsion system, the airframe and the flight mission.

In the Special Research Programme (SFB) 255 this subject is studied in a joint effort between the Institute of Flight Propulsion and the Institute of Flight Mechanics, Technische Universität München.

A real-time research flight simulator is installed to study hypersonic flight characteristics, the interaction of dynamic aircraft and propulsion system behaviour as well as off-design procedures and engine failure handling (Fig. 1). Due to its comparatively simple adaptability to changes in configuration, real-time simulation is considered, an important initial stage to flight tests. Subsequently the basics and the possibilities of a combined engine/aircraft simulation for hypersonic flight vehicles will be discussed.

2. Engine modelling

The reference propulsion system of the considered generic TSTO-concept is composed of a rectangular intake and diffuser, a two-spool-low-bypass turbofan engine, a closure mechanism to seal the turbo engine section during the ramjet mode and protect it from the high heat loads in the upper flight Mach number range, a reheat/ram combustor and a 2D nozzle with an afterbody expansion ramp (Fig. 2). [1]

The quality of an engine simulation strongly depends on the accuracy of the modelling of the physical processes within the engine. Special emphasis was laid on the description of thrust nozzle and intake characteristic at design and off-design conditions.

In order to create a compatible description of all forces acting on airframe and propulsion system an overall bookkeeping system was defined. All effects caused by the engines are summarized in the propulsion data set (net thrust, F_{net}), while the forces acting on the defined airframe are contained in the aerodynamic data set. Fig. 3 shows schematically the force and moment bookkeeping system for the proposed highly integrated propulsion system.

Air Intake

The performance of a hypersonic propulsion system is considerably affected by the operation of the intake. Following the concept of a combined cycle turbo ramjet propulsion system there are basically two different working modes. During turbojet operation (Mach numbers up to 3-4) the matching of the intake air flow and the turbo engine demand is of main importance. The best possible intake pressure ratio, an optimized mass flow adaptation and a minimum of compressor entry flow distortion is required. Therefore the boundary layer of the lower forebody of the aircraft is diverted through an additional duct. With increasing flight Mach number (ram-mode) the mass flow determines the intake geometry. Maximum pressure recovery is not a design issue since the total pressure of the free flow has to be reduced by the intake shock system in order not to exceed the structural limits. Fig. 4 shows typical values of the pressure recovery of supersonic inlets.

The intake as described in the bookkeeping system excludes the precompression along the forebody. A change of the angle of attack results in different precompression behaviour and therefore in a different intake entry pressure and Mach number. The intake itself feels no change in flow direction. The proposed mixed compression intake induces four shocks in turbo engine operation. Two external oblique shocks are generated by the movable ramps, one oblique shock is generated by the cowling and the final "normal" shock is located downstream of the throat. With the closed two-position diverter flap, an extra external oblique shock is formed. Mass flow control and engine intake matching is obtained by the control of the ramp positions (see Fig. 5), by the diverter mode (open/closed) and by a bypass diverting undesired massflow behind the intake throat.

Single Expansion Ramp Nozzle (SERN)

The exhaust nozzle for hypersonic aircraft represents an important part of the propulsion system. Throughout the flight mission from low subsonic to hypersonic speeds (Ma > 5+) the nozzle system has to work over a wide range of different operating conditions. For example the nozzle pressure ratio varies from three at take-off to about 800 at maximum flight Mach number. To obtain high installed performance over this range of pressure ratios a geometric highly flexible yet highly integrated exhaust nozzle system is required. The 2D single expansion ramp nozzle is considered most suitable for hypersonic application and was chosen as the baseline exhaust system[24]. High demands are made on nozzle performance at low and high Mach numbers. Whereas at high flight Mach numbers only small changes in nozzle performance will result in large deviations of net installed thrust (1% reduction in nozzle performance will result in a loss of net installed thrust of about 4%), the situation is different in the transonic flight regime. Large changes in thrust vector are associated with the concept of asymmetric thrust nozzles, designed for high Machnumber operation (Fig. 6). This behaviour considerably influences the flyability of the aircraft in the transonic flight Mach number region. For the study of the interference between the main nozzle flow and the ambient flow a generic windtunnel model (Fig. 7) was tested by MTU-DASA München in the Trisonic Windtunnel (TMK) and in the Hypersonic Windtunnel (H2K) at the DLR in Cologne for a joint research programme with the Institute of Flight Propulsion (TUM). Fig. 8 and 9 show comparisons between calculated and measured wall pressure distributions along the upper nozzle wall including the expansion ramp (Fig. 8) and along the lower flap (Fig. 9) for a range of flight Mach numbers, angles of attack and pressure ratios [16].

Studying the effects of different parameters on the performance of the exhaust system and describing realistically the change of gross thrust vector over a flight mission from transonic to hypersonic Machnumbers, the numerical flow field analysis was carried out over a wide range of different operating conditions: Π = 3 - 800, Mach: 1.6 - 6.0 and $\alpha = 0° - 8°$.

For the windtunnel model Fig. 10 shows the change in thrust coefficient $c_{fg,x}$ as a function of flight Machnumber and pressure ratio $\Pi = p_7/p_\infty$. The large thrust vector variations that occur at transonic flight Machnumbers are mainly caused by expansion losses of the nozzle flow and the increasing external drag of the lower nozzle flap. This basic gross thrust vector behaviour is independent of the chosen pressure ratio Π, though increasing Π compensates, up to a certain amount, the losses caused by the low local pressure distribution along the flap.

3. Engine simulation:

Within these studies three methods are used to describe the steady state and dynamic engine behaviour numerically:

Performance analysis: Firstly there is the performance analysis ("synthesis calculation"). To enable the computational description of an engine system, the propulsion system is subdivided into different components such as: intake, compressors, combustion chambers, turbines, thrust nozzles, etc.. Each component is characterized by a distinct physical behaviour. The interaction of the various engine parts/modules determines the steady state performance and transient operation of the total propulsion system. Within each module the basic physical behaviour is described by an appropriate set of equations and/or characteristic maps. The engine components are coupled with each other not only via the laws of mass-, momentum- and energy conservation but also via the engine control system. Therefore the recombination of different components, forming the propulsion system, results in a nonlinear, coupled set of equations, which has to be solved by means of an iterative numerical procedure (e.g., Newton-Raphson). The quality of the performance analysis strongly depends on an accurate modelling of the basic physical processes within a single engine component. For example, the intake and the nozzle of airbreathing hypersonic aircraft propulsion systems are characterized by the high degree of engine/ airframe integration, by the high requirements on geometric flexibility and thrust performance, by the complex flow fields phenomena within the components and the wide area of largely different operating conditions. The accurate modelling of the underlying physics is far too complex and time consuming to be done within the performance analysis itself. The performance- and operating-behaviour of these components is therefore usually described by so called characteristic maps or characteristic lines, which are based on data provided by experiments and/or theoretical methods. Creating accurate component maps is one of the key issues in simulating hypersonic airbreathing engines.

State Space Model: Another method to analyse the dynamic behaviour of a propulsion system is the "state space model", that is derived from system analysis. The non-linear, time variant dynamic engine behaviour is described by a general vector differential equation system. By linearization of this system near a reference point a time invariant equation system is created, that can describe the dynamic behaviour fairly well. The matrix elements of this equation system can be either derived from a theoretical or experimental system analysis or a performance analysis program. Depending on the order of the set of equations it is possible to solve this linearized system in real-time.

Function Generator Method: The most common method to realize an engine real time simulation is the so called "method of function generators".

Within this method the parameters describing the working process of the engine (temperatures, pressures, massflows) are represented by functions of regulating parameters. These parameters can be for example the gas generator speed or the flight Mach number. These functions are "generated" by interpolating results of either a performance analysis or experiments. The loss of flexibility in this method is set off by the increase in calculation speed.

A control system adjusts the engine parameters to the pilot's or auto pilot's input. Furthermore certain component limits have to be observed, as there are fixed maximum temperatures for compressor exit and combustion chamber or maximum pressure levels for the ramjet combustion chamber. A variable maximum fuel flow increase, for example, prevents compressor surge and the superheating of the turbine. During turbo mode the afterburner is operated approximately stoichiometrically. At ramjet operation an overstoichiometric combustion is allowed in order not to exceed the maximum nozzle entry temperature and still deliver the required thrust.

As an example Fig. 12 shows the net thrust $F_{net,x}$ versus the flight Machnumber of the presented hypersonic combined propulsion system as a result of steady state performance analysis. The lower nozzle flap was adjusted to achieve the minimum possible gross thrust vector angle. Besides lines of constant dynamic pressure and constant flight altitude also the lines of constant net thrust vector angle β are shown.

Fig. 11 shows the engine dynamic in turbojet mode during acceleration at a Machnumber of 0.9 and an altitude of 10000m from idle to maximum turbo engine power. Among the most important dynamic effects influencing the propulsion system transient behaviour are rotor inertia, heat transfer, and nozzle resp. intake actuating speed. In this study, rotor inertia and a simplified model for actuating speeds are implemented.

4. Engine/Aircraft interactions:

The flight mechanical studies were performed with a program that is based on a six degree of freedom model. The aircraft model is based on a reference TSTO concept as presented in (2,24,25,28). The nonlinear control system of the aircraft is derived from other aircraft.

The simulation code is set up on a computer connected to a flight simulator as shown in the simplified scheme in Fig. 14. A computer converts the pilot's stick and pedal forces into input values for the simulation.

Efforts have been made in the area of man machine interface development to ease pilot's tasks as far as possible. A picture of the cockpit arrangement is shown in Fig. 15. Special tools like a visual tunnel for track guidance and new display techniques are examined and optimized with the flight simulator (26).

As further subject the influence of the dynamic behaviour of the propulsion system on aircraft dynamics was studied. During the flight mission through the transonic regime the acceleration from Mach 0.9 at the altitude of 10000 m is an important manœuvre. The aircraft accelerates from horizontal trimmed flight to about Mach 1.64 followed by a climb. Starting the acceleration the power lever is increased from the trimmed position to maximum and the afterburner is ignited. The fuel flow in the afterburner is increased approximately up to stoichiometric combustion. All flight manœuvres will be performed by a complex nonlinear control system, allowing the aircraft to follow the precalculated flight trajectory.

Fig. 16 shows a comparison between the steady state and the dynamic engine simulation. The dotted lines indicate the steady state values, the solid lines the values for a dynamic engine simulation. In the diagram at the bottom of this figure the tendency of the engine overshoot can be seen. Furthermore a retardation of about one second in thrust increase is recognizable. This is mainly due to the mass inertia of the rotating parts in the turbo engine. After about 5 seconds a steady state is reached.

The dynamic behaviour of the aircraft is influenced to some extent by the changes in thrust forces and direction during the acceleration. Oscillations are diminished by the flight control system. Due to the delayed thrust changes the curves are smoother for the dynamic engine behaviour. The changes in attitude are smaller and retarded. This can be seen in the changes of the angle of attack α and the acceleration $\dot{V}$. In consequence the necessary elevator deflection η is smaller and slower. Therefore the dynamic engine behaviour smoothes the reaction of the aircraft caused by the power lever step input despite the tendency of the engine to overshoot.

During the raise of the fuel flow in the afterburner the influence of the dynamic engine behaviour is negligible.

5. Engine failure:

It is not sufficient to evaluate the feasibility of a transport system by considering regular flight operation alone. Furthermore it is inevitable to remember that every technical system can fail and therefore the consequences of a propulsion system failure have to be taken into account. The controllability of the aircraft is a key criterion for the system design.

For a first estimate the most critical point of the flight envelope for an engine failure has to be found and studied. Due to very high thermal loads and a reduced effectiveness of rudder and aileron the high Mach numbers must be examined.

Two major scenarios are conceivable. In case of a failure in the fuel supply system the combustion process would stop ("flame out" scenario). Even if only one engine fails the mission must be interrupted. Due to safety reasons the fuel flow of all working engines will be reduced. In order to minimize thermal and structural loads the dynamic pressure must be diminished as fast as possible and a descend at a lower dynamic pressure will be initiated.

A failure in the control system of either the intake or the nozzle system might result in an "unstart" situation, i.e., the intake would be choked.

In this case it seems probable that all engine intakes will be affected. For detailed information three dimensional calculations will be necessary, in the present study it was assumed that all five intakes choke the same way.

To predict the consequences of these failures 2D-Navier-Stokes calculations have been carried out, analysing the behaviour of the intake and nozzle including the effects of the flow field bypassing the cowling.

Fig. 13 shows the resulting forces of the propulsion system for nominal operation, an engine "flame out" and an "intake choking". The intake entry Mach number is 5.0, i.e., a flight Mach number of close to 6.0 at an angle of attack of 5.8°. Intake-, lip-, cowling/flap- and nozzle force vectors are indicated as well as the resulting net thrust vector.

In case of flame out, the intake is not affected, the resulting intake forces are therefore unchanged. The gross thrust is low while the gross thrust vector angle β is nearly unchanged. As net "thrust" the engine produces small drag and lift forces.

The choked intake is the worst scenario considered. Due to a detached shock the intake produces a large amount of drag. The pressure force component is high so that intake as well as cowling produce considerable lift. The massflow through the engine is low (only 20% of the nominal massflow in this example) so that the nozzle hardly produces any thrust. The shock system in the nozzle leads to a relatively high lift component. The resulting propulsion force is large lift and drag. On top of that the pressure forces acting on the intake lip are high, may be destructive. An uncontrolled unstarted intake should be avoided under all circumstances.

The effects of the propulsion system failures on the aircraft have been studied using the flight simulator.

The scenario of an all engine flame out at Mach 6.0 at a flight level corresponding to a dynamic pressure of 50 kPa is shown in Fig. 17.

The preceding engine calculations show an instantaneously change in thrust forces at the nozzle. At an engine failure the dynamic pressure has to be diminished as fast as possible to reduce the structural and heat loads on the propulsion system. Therefore the aircraft's flight control system performs a step input in the pitch moment equilibrium. The ability of the control system to cope with the change highly depends on the effectiveness of the elevator which decreases with increasing altitude. The forces at the intake decline slowly as its momentum force depends linearly on the dynamic pressure. The moment at the intake even decreases in the first few seconds as a reaction on the change in angle of attack.

A possible flight manœuvre is shown in Fig. 17. The aircraft decelerates from Mach 6.0 to Mach 5.0 in about one minute and climbs to an altitude of about 30000 m. In consequence the dynamic pressure declines from 50 kPa to 20 kPa. The maximum acceleration in vertical direction is less than 1.35 g. The maximum elevator deflection is about 5 degrees from trimmed value and the change of angle of attack is about 3 degrees. All these parameters are within the limits of the design specification. When the desired dynamic pressure is reached the aircraft returns on a glide path keeping constant the dynamic pressure. Depending on the failure the engines might be restarted.

Conclusion:

As a result of this presentation it is shown that in a realistic flight mechanical calculation resp. simulation of a hypersonic aircraft the dynamic engine behaviour has to be considered.

Furthermore it is necessary to study the vehicle reaction on different kinds of engine failures. Within the scope of the engine simulation, e.g., a flame out and/or an all-engine choked situation were investigated by Navier-Stokes calculations. The integration of the numerical results in a research flight simulator has shown that the reference TSTO hypersonic aircraft is controllable even in emergency situations.

Acknowledgements:

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Total First Stage Dry Mass	167500 kg
GTOW Second Stage	115000 kg
Take Off Mass	410000 kg
Vehicle Length	82.4 m
Span	45.2 m
Reference Wing Area	1658 m^2

Table 1: Reference hypersonic Two-Stage-To-Orbit (TSTO) concept. Selected data

Number of Engines	5
$(p_{t3}/p_{t2})_{max}$	12
$T_{t4\,max}$	1850 K
$T_{t7\,max}$	2800 K
F_{net} (M=0, H=0km, dry)	445 kN
F_{net} (M=1.2, H=10km, reh.)	260 kN

Table 2 : Reference concept for integrated combined turbo ramjet propulsion system. Selected data

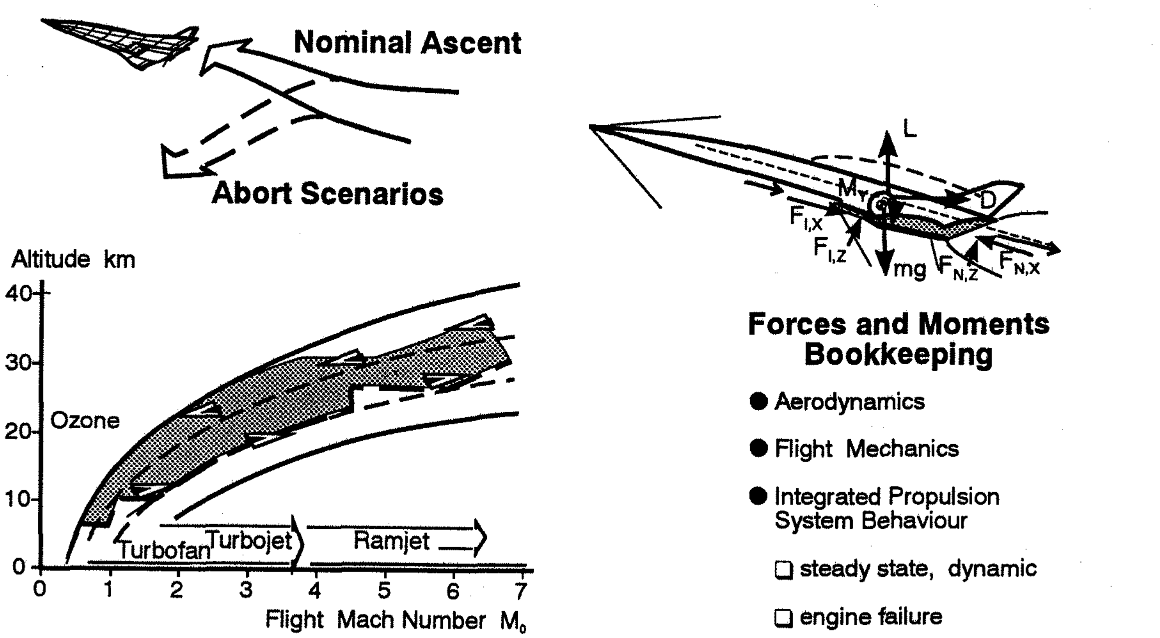

Fig. 1: Lower stage ascent trajectory of a Two-Stage-To-Orbit transport system and main problems

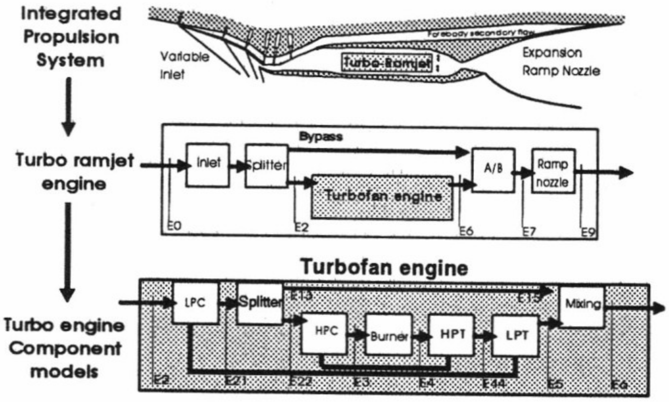

Fig. 2: Integration and simulation model of combined turbo-/ramjet propulsion system for steady state and dynamic engine behaviour

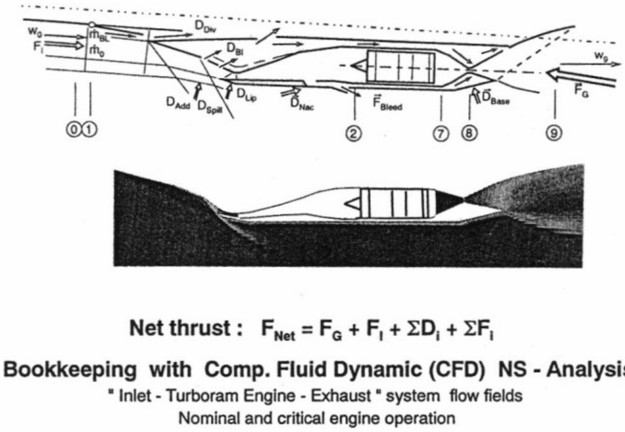

Fig. 3: Forces and moments bookkeeping for the hypersonic vehicle / propulsion system with application of Computational Fluid Dynamics

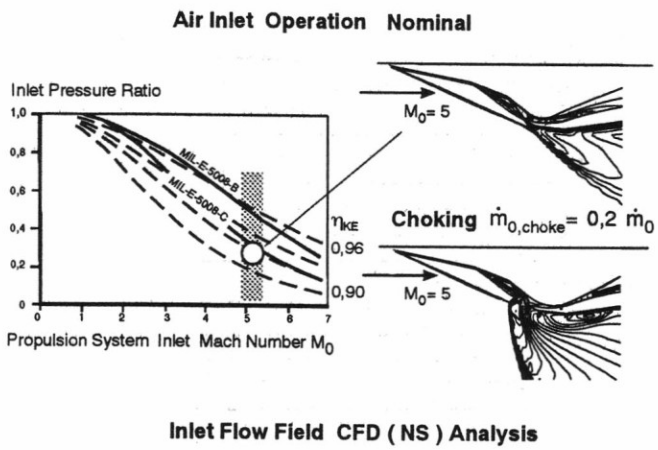

Fig. 4: Total pressure ratio for hypersonic propulsion air intake in nominal and critical operation behaviour

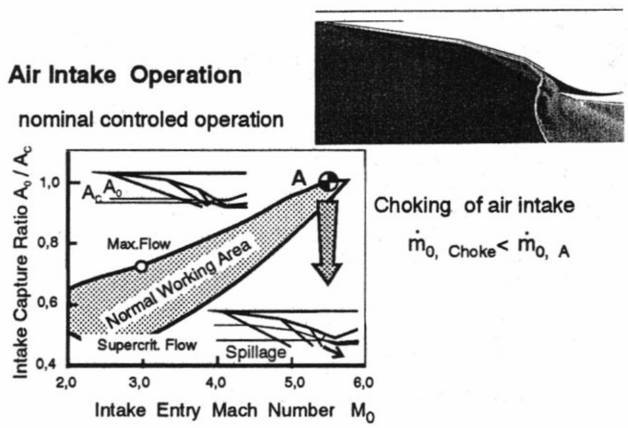

Fig. 5: Capture area resp. massflow for the intake system in nominal/choked operation

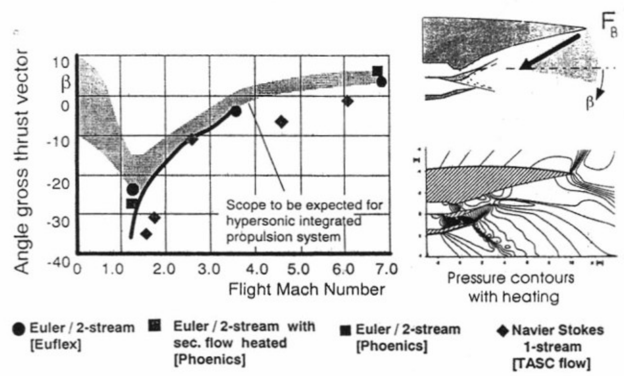

Fig. 6: Gross thrust vector angle of SERN nozzles calculated by different CFD codes

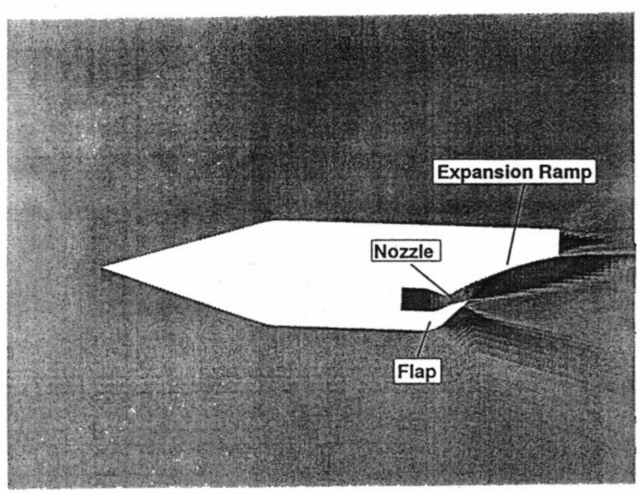

Fig. 7: Nozzle/afterbody CFD-windtunnel model for comparison CFD technique / experiment

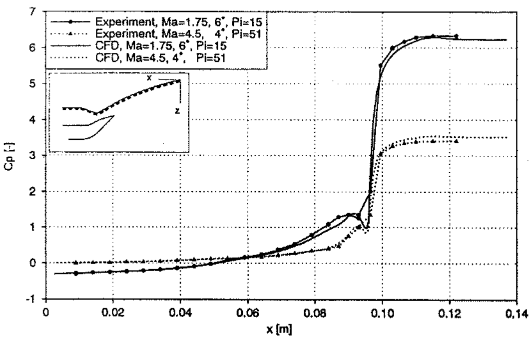

Fig. 8: Expansion ramp nozzle with experimental and CFD results. Local pressure coefficient c_{pi} along expansion ramp

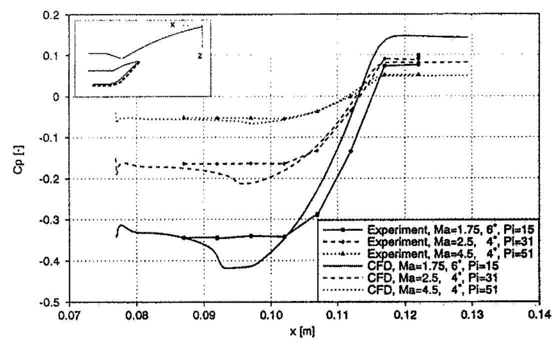

Fig. 9: Expansion ramp nozzle - local pressure coefficient c_{pi} along nozzle flap

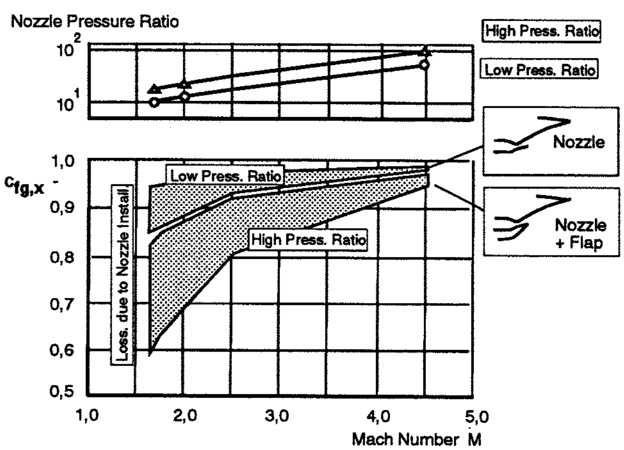

Fig. 10: Gross thrust coefficient $c_{fg,x}$ as function of flight Mach number and nozzle pressure ratio

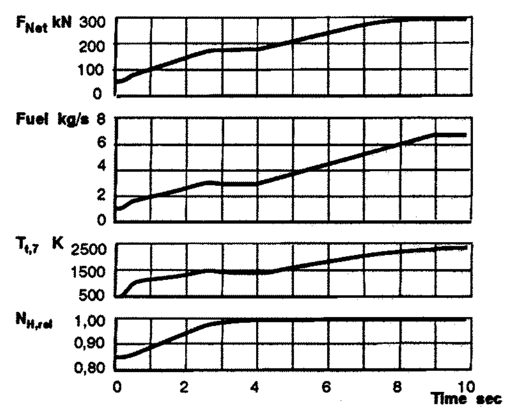

Fig. 11: Typical engine acceleration at M_∞= 0.9 and H=10000m: N_H = 85% to 100% and Φ=1.0

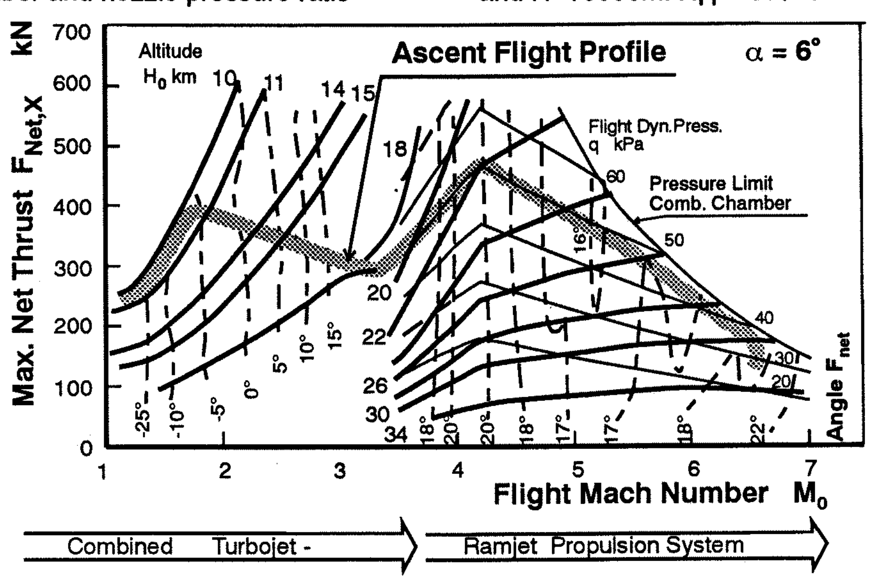

Fig. 12: Max. net thrust $F_{Net,x}$ and angle σ of net thrust vector - constant aircraft angle of attack α=6°

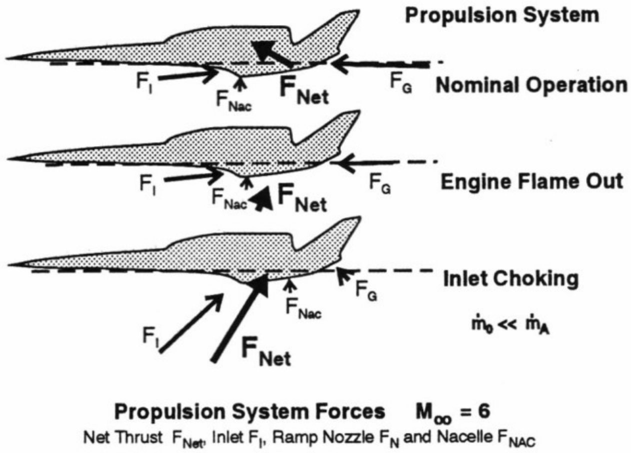

Fig. 13: Main propulsion system forces F_i and net thrust vector F_{Net} in nominal and failure operation with flame out or unstarted intake

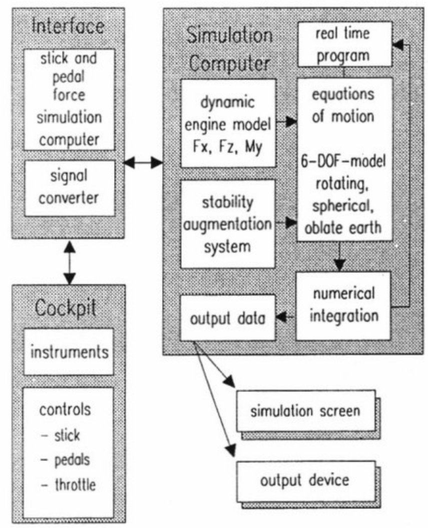

Fig. 14: Scheme of LFM-research flight simulator

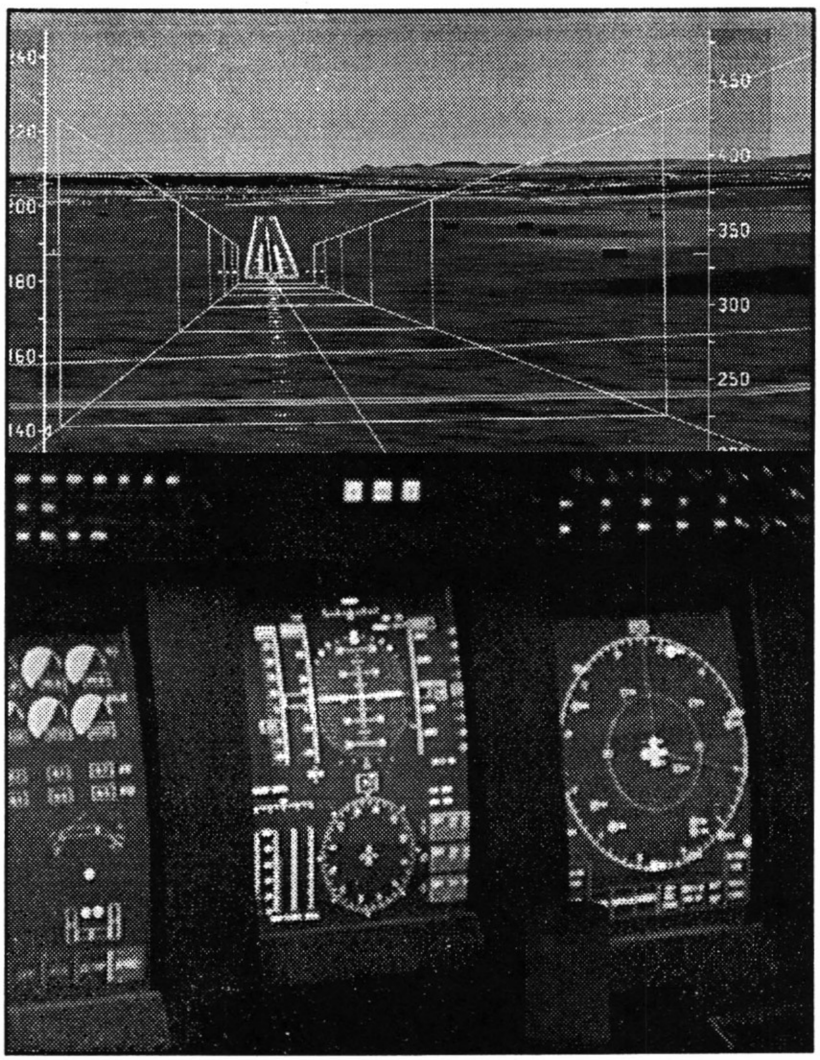

Fig. 15: Research flight simulator (Institute of Flight Mechanics and Flight Control) with visual flight tunnel

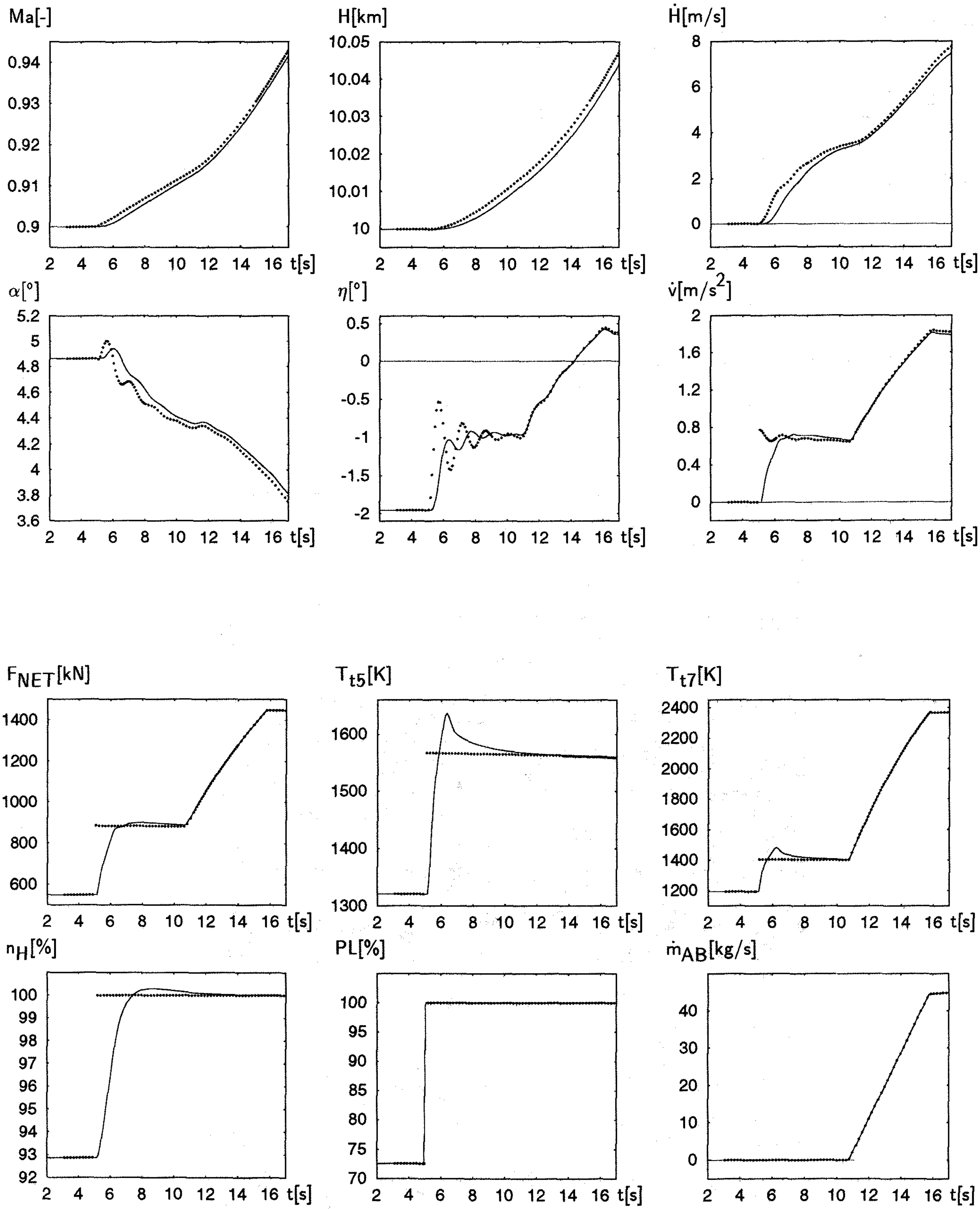

Fig. 16: Hypersonic TSTO-vehicle. Engine acceleration from cruising position to max power. Influence of engine transient behaviour on aircraft flight dynamic. Altitude 10000m, flight Mach number: 0.9 (solid lines: dynamic engine model, dotted lines: steady state values)

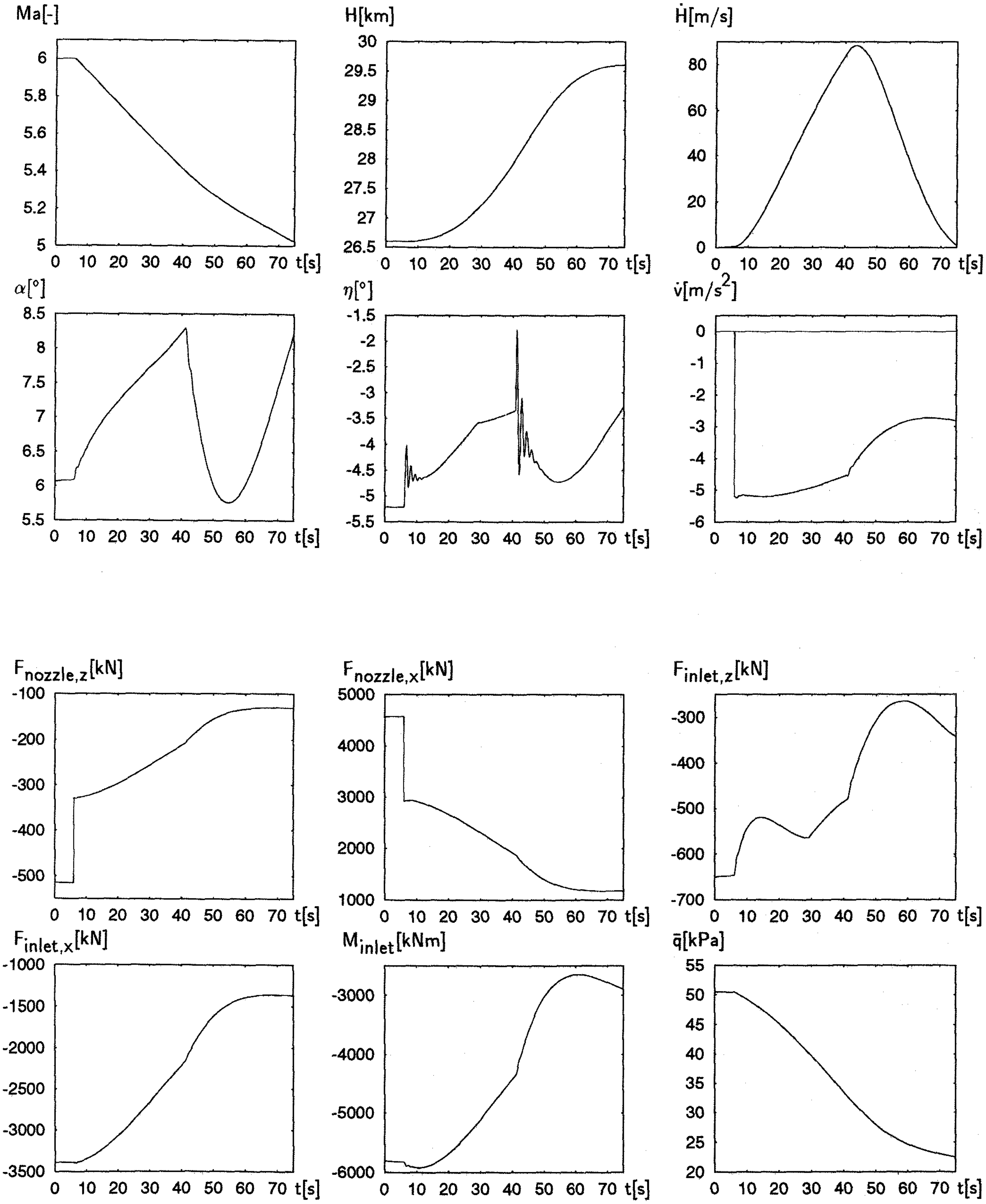

Fig. 17: Hypersonic vehicle during critical flight operation with engine failure (flame out). Altitude: 26600m, Flight Machnumber: 6.0