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Installed performance evaluation of an air turbo-rocket expander engine

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ABSTRACT

The propulsion plant of a prospective supersonic cruise aircraft consists of an air turbo-rocket expander and a dual-mode ramjet. A comprehensive numerical model was constructed to examine the performance of the air turbo-rocket during the supersonic acceleration of the vehicle. The numerical model comprised a one-dimensional representation of the fluid paths through the dual-mode ramjet, the air turbo-rocket combustor, the regenerator and the airframe-integrated nozzle, whereas the turbomachinery and the air turbo-rocket bypass were included as zero-dimensional models. The intake operation was based on the results of time-averaged Euler simulations. A preliminary engine analysis revealed that the installation effects restricted significantly the operational envelope, which was subsequently extended bypassing the air turbo-rocket. Hence the engine was throttled varying the mixture ratio and the fan compression ratio. Nevertheless, the performance was optimal when the demand from the air turbo-rocket matched the intake air flow capture. The heat recovery across the regenerator was found critical for the operation of the turbomachinery at low speed. The transition of the air turbo-rocket to ramjet operation was identified at Mach 4.5. During this regime, the propulsion plant was rather insensitive to the mixture ratio and was throttled with the air turbo-rocket throat area.

1. Introduction

The air turbo-rocket expander under investigation is sought as the acceleration engine for a Mach 8 cruise aircraft [28,29]. The mission of the air turbo-rocket engine is to accelerate from take-off to Mach 4.5 at 24 km of altitude, where a dual-mode ramjet (DMR) accelerates further to cruise speed [20]. The hydrogen-fueled propulsion plant consists of six air turbo-rockets and a dual-mode ramjet mounted in parallel and highly integrated within the airframe. The use of the terms air turbo-rocket and air turbo-ramjet is often subject to controversy in the literature. Following the distinction made by Kozlaykov [19], the gas generator of an air turbo-ramjet follows a Brayton cycle, whereas the fuel across the heat exchanger and the turbine which powers the fan follows a Rankine cycle in the air turbo-rocket. In this sense, referring to the air turbo-rocket as expander is redundant, but serves to distinguish from the air turbo-rocket with gas generator, a term frequently used to designate the air turbo-ramjet. Each of the two engine bays, sideways of the aircraft, comprise three air turbo-rockets, Fig. 1. The turbomachinery of each air turbo-rocket expander consists of a two-stage counter-rotating fan and a hydrogen pump driven by a counter-rotating hydrogen turbine. The turbine is modeled as a single unit despite that different stages drive the pump and the fan, depicted in Fig. 2. The identification of the control inputs and the performance of the power plant is essential for the evaluation of the aircraft mission and, in addition, for the design of the aircraft flight controller [34]. In this respect, the air turbo-rocket cycle which best meets the mission requirements of the aircraft was identified in a previous study by Rodríguez-Miranda et al. [27]. Nonetheless, the uninstalled performances (integration effects were neglected) of the air turbo-rocket which resulted from that previous analysis did not suffice to assess the aircraft mission.

An extended model addressing the integral propulsion plant of the aircraft, i.e. both high and low speed inlets, bleeding system, air turbo-rockets, dual-mode ramjet, regenerator and the airframe-embedded nozzle, was developed in order to compute the installed performances in the supersonic regime. The model was based on EcosimPro [32] and the set of libraries of the European Space Propulsion System Simulation (ESPSS) [10,25]. Ad hoc models of the nozzle, the dual-mode ramjet, the air turbo-rocket bypass system and the regenerator were developed. The one-dimensional flow through the dual-mode ramjet, the

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Nomenclature

A	transversal area	m^2
a	speed of sound	$\mathrm{m\,s^{-1}}$
B	bypass ratio	
C_p	heat capacity at constant pressure	$\mathrm{m^2\,s^{-2}\,K^{-1}}$
C_x	spillage drag coefficient	
D_h	hydraulic diameter	m
e	total energy: $e = h^0 - pv$	$\mathrm{m^2\,s^{-2}}$
G	Gibbs potential	$\mathrm{kg\,m^2\,s^{-2}}$
h	enthalpy	$\mathrm{m^2\,s^{-2}}$
I_{sp}	specific impulse	$\mathrm{m\,s^{-1}}$
k	thermal conductivity or sensitivity	$\mathrm{kg\,m\,s^{-3}\,K^{-1}}$
N	number of moles	mol
p	pressure	$\mathrm{kg\,m^{-1}\,s^{-2}}$
R_g	ideal gas constant	$\mathrm{m^2\,s^{-2}\,K^{-1}}$
T	temperature	K
T_{sp}	specific thrust	$\mathrm{m\,s^{-1}}$
T_w	wall temperature	K
v	velocity	$\mathrm{m\,s^{-1}}$
z	altitude	m

Acronyms

AR	aspect ratio
ATR	air turbo-rocket
DMR	dual-mode ramjet
HSI	high speed intake
LSI	low speed intake
MR	air-to-fuel ratio
TPR	total pressure recovery

Greek symbols

α_c	intake mass capture ratio	
β	ratio of flow areas	
χ	ratio of mass flows	
η	adiabatic efficiency	
γ	ratio of heat capacities	
μ	viscosity	$\mathrm{kg\,m^{-1}\,s^{-1}}$
π	pressure ratio, number π	
ρ	density	$\mathrm{kg\,m^{-3}}$
ξ	friction factor	$\mathrm{m^{-1}}$

Sup-/subscripts

0	stagnation quantity
∞	free-stream conditions

Other symbols

$\dot{m}$	mass flow	$\mathrm{kg\,s^{-1}}$
$\dot{q}$	heat flux	$\mathrm{kg\,s^{-3}}$
$\mathcal{F}$	thrust	$\mathrm{kg\,m\,s^{-2}}$
$\mathcal{F}_u$	uninstalled thrust	$\mathrm{kg\,m\,s^{-2}}$
$\boldsymbol{u}$	control vector	

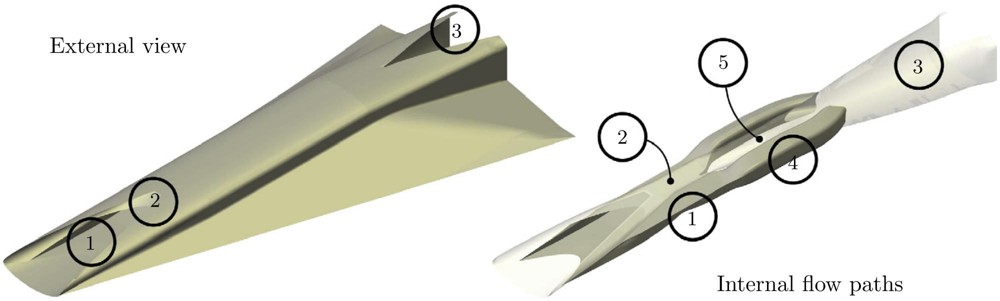

Fig. 1. Rendering of the Mach 8 cruise aircraft: **1** low speed intake, **2** high speed intake, **3** nozzle, **4** ATR duct, **5** DMR duct.

air turbo-rocket combustion chamber and the nozzle was computed considering the allocated flow areas along these components. The importance of the airframe-intake integration in the supersonic regime is well known and has been addressed since long time [4], here time-averaged Euler calculations provided the performances of the high and the low speed intakes in the range of flight speeds from Mach 1.5 to 4.5 [23,24].

2. Numerical model

Fig. 3 sketches the flow paths through the aircraft propulsion plant. In the intake, at stations 21 and 20, the inlet air flow is split into two streams to feed the ducts of the air turbo-rocket and the dual-mode ramjet respectively. Hence, in the numerical model, two distinct intakes are considered, together with their respective performance, i.e. mass capture and total pressure recovery: the low speed intake (LSI, stations 10 to 211) and the high speed intake (HSI, stations 10 to 80, i.e. including the ramjet isolator). The exhausts of both engines and the bypassed air flow come together at the entrance of the nozzle (stations 802 and 812).

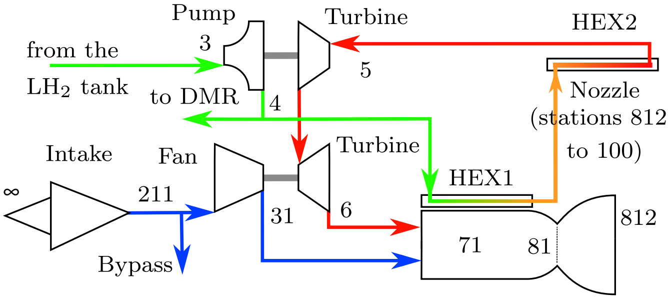

Fig. 2. The air turbo-rocket expander cycle.

The low speed intake discharges at the fan inlet plane (station 211). The cross areas at each station are listed in Table 1. The total cross section allocated to the air turbo-rocket engines (stations 211 and 31) is 10% larger than the cross section of the throat when fully open (station 81). The inviscid time-averaged Euler calculations in the range of flight Mach numbers 1.5 to 4.5 by Meerts et al. [23,24] yielded the mass capture and total pressure recovery through the low and high speed intakes displayed in Fig. 4, as well as the outlet Mach number and the spillage drag of the high speed intake listed in Table 2. The total pressure recovery across the low speed intake was computed for the most favorable