Title: Air Intake Design for the Acceleration Propulsion Unit of the LAPCAT MR2 Hypersonic Aircraft.

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Abstract:

A supersonic air intake has been designed for the acceleration propulsion unit of the LAPCAT-MR2 hypersonic aircraft. This auxiliary propulsion system powers the LAPCAT MR2 aircraft for takeoff, acceleration up to transition to dual-mode ramjet-powered flight at Mach 4 and landing. Development of this air induction system has been based on the reverse engineering of the XB-70 air induction system and has been driven by the need to comply with the vehicle external layout and available internal volume. The design process for the new air induction system has been segmented in five phases:

- The reverse engineering of the XB-70 air intake
- The implementation of a supersonic air intake design software
- The validation of the intake integration strategy
- The iterative integration of the new air induction system onto the LAPCAT MR2 aircraft
- The final assessment of the designed air induction system at a key operation point

First, a reverse engineering analysis of the XB-70 air intake has been performed. The XB-70 air intake and its operation schedule have been reconstituted and a CFD analysis campaign throughout the whole flight domain has consequently been executed using the DLR TAU-Code solver. The CFD simulations results have been found to agree with experimental flight and wind-tunnel data. In particular, the demarcation between started and unstarted operation modes could be correctly reproduced as shown in Fig. 1.

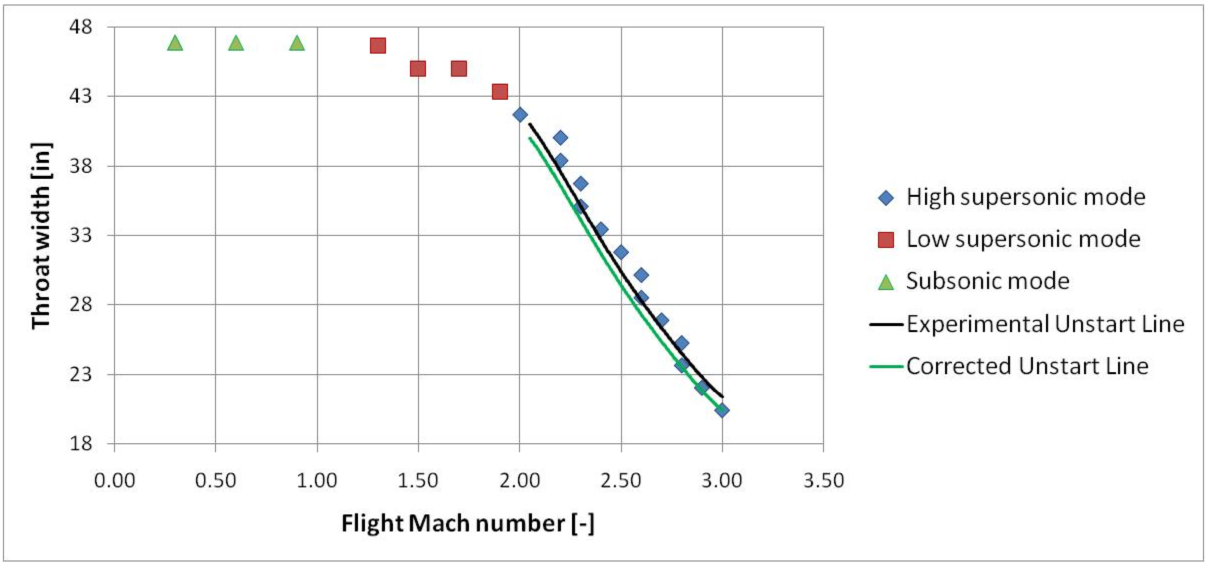

Figure 1: XB-70 Aircraft Air Intake Reverse Engineering
Experimental unstart line and best performing configuration from CFD

Moreover, total pressure recovery figures along the whole range of flight conditions have been found to be consistent with experimental flight data, as shown in Fig. 2.

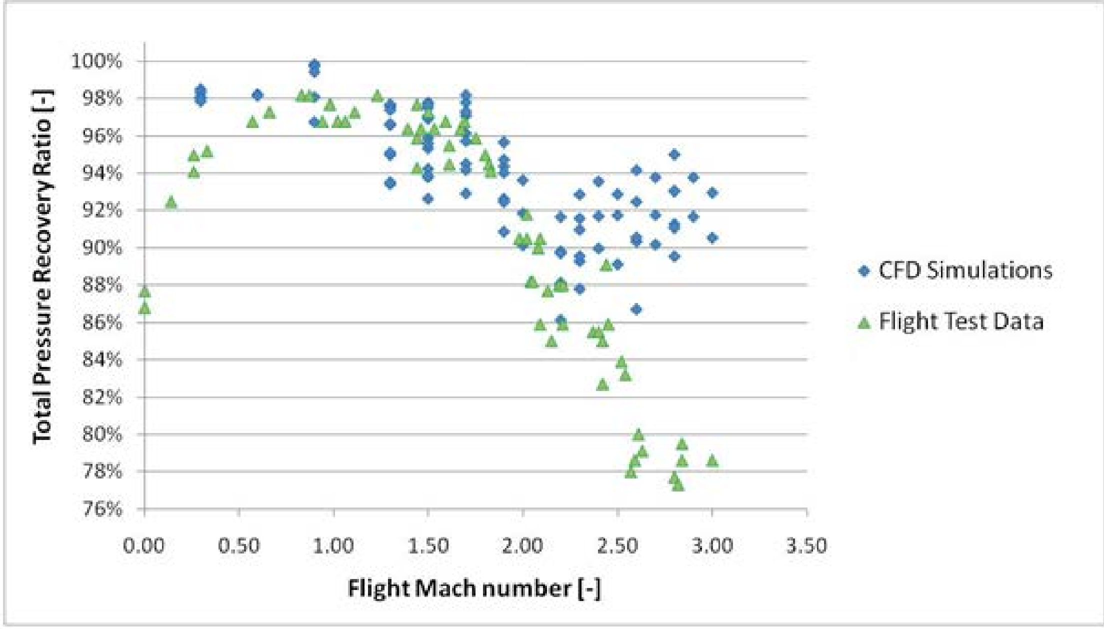

Figure 2: XB-70 Aircraft Reverse Engineering
Total pressure recovery ratio from experimental flight data and CFD simulations

Consequently, the CFD analysis process applied has been validated for the study of supersonic supercritical air intakes. In addition, the CFD analysis of the XB-70 air induction system has led to the identification of the boundary layer control system as the key feature that allows proper operation of the air intake along the whole range of flight regimes.

The second phase of the study has been dedicated to the implementation of an air induction system design software. A shock pattern propagator allows the evaluation of the flow topology induced within the supersonic diffuser for a given configuration and throat and subsonic diffuser state may then be evaluated. Together with empirical estimates of the maximum area ratio at the throat and taking into account the need for boundary layer control and subsequent wall suction, an optimisation algorithm attempts to converge towards an air induction system configuration that best meets device volume constraints and performance targets.

At the same time the third development phase has been undertaken, aiming at the selection of a feasible implementation layout for the new air induction system onto the LAPCAT MR2 vehicle. Since the external layout of the vehicle has been optimised for hypersonic flight and may not be modified significantly by the installation of the low speed air intake, the only possible design layout has been identified as the implementation of a derivation from the dual-mode ramjet intake.
Hence, a rectangular opening has been drawn onto the LAPCAT MR2 dual-mode ramjet intake, based on the mass flow requirements estimates of the low speed propulsion engines and sound assumptions regarding flow topology. An illustration of both the original dual-mode ramjet intake and its modification for the installation of the low speed air induction system are provided as Fig. 3 and Fig. 4 below:

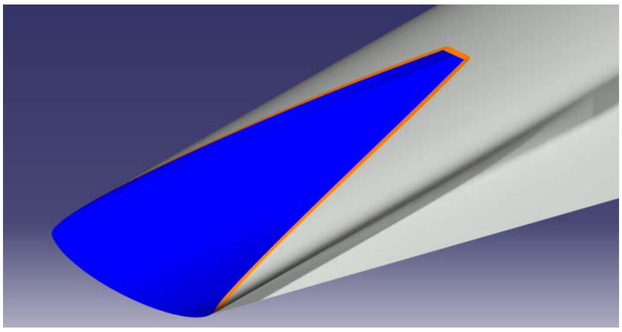

Figure 3: LAPCAT MR2 Dual Mode Ramjet Intake
Dual-mode ramjet intake topology with ramjet walls in blue and ramjet intake edges in orange

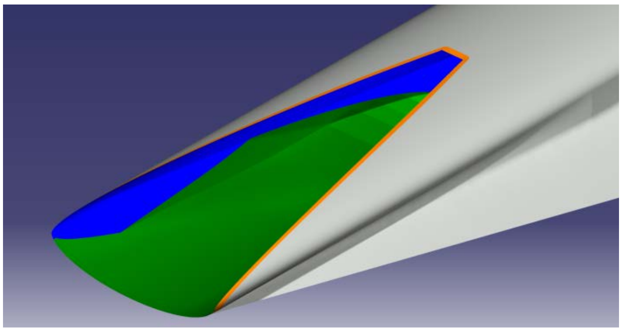

Figure 4: LAPCAT MR2 Low Speed Intake Derivation
Low speed air intake derivation within the dual mode ramjet intake with ramjet walls in blue, ramjet intake edges in orange and low speed air intake in green

A CFD analysis of this layout has then been performed throughout the whole flight domain of the low speed propulsion in order to ensure the ramjet intake derivation design is operable in all conditions. Since the first results of this analysis were showing poor performance due to dual-mode ramjet unstart at Mach 3 and lower speeds, a compromise between the need for hypersonic cruise performance and the need for proper operation of the acceleration unit. The installation of a variable geometry crotch on the dual-mode ramjet intake has been identified as a feasible solution and its performance for various configurations assessed through CFD analysis. Illustrations of both the original crotch configuration and one of the variable geometry crotch configurations tested are provided as Fig. 5 and Fig. 6 below:

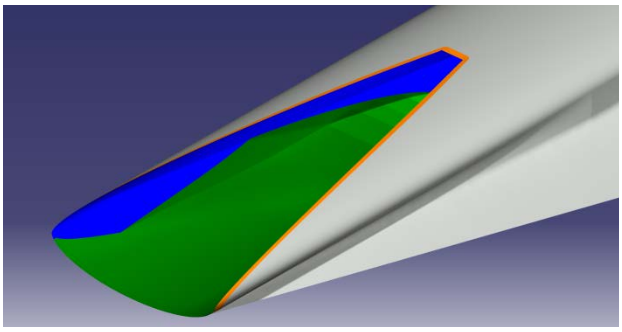

Figure 5: LAPCAT MR2 Dual Mode Ramjet Crotch
Original dual mode ramjet crotch design for hypersonic cruise

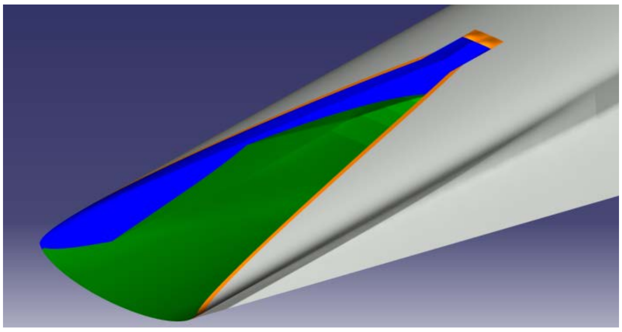

Figure 6: LAPCAT MR2 Dual Mode Ramjet Crotch
Modified dual mode ramjet crotch design for proper operation of the d low speed air intake

The analysis has led to the conclusion that several crotch configurations allow early dual-mode ramjet unstart avoidance and hence meet mass flow requirements with a significant margin that allows the usage of a wall suction-based boundary layer control system. Consequently, the rectangular opening layout has been selected for further development in combination with a variable geometry dual-mode ramjet crotch.

Unfortunately, the dual-mode ramjet has been found to induce significant distortion in the flow diverted towards the low speed air intake and the CFD-analysis of the first software-generated air intake configuration has led to the observation of multiple unexpected undesirable flow features within the air intake duct. Those observations have led to the planning and execution of an additional iterative design process for the integration of the low speed air induction system on the LAPCAT MR2. Throughout this additional design loop, design software-generated air intake configurations have been CFD-analyzed in order to identify any potential distortion-induced undesirable flow feature. For all every undesirable flow feature detected, new constraints have been input to the design software until finally converging towards an air intake configuration that no longer exhibits distortion-induced Mach stems or vortices.

Finally, the last phase of the development has been dedicated to the complete assessment of the last most promising air intake configuration. A complete CFD analysis of this configuration has been performed for the Mach 3 operation, including the modelling of the boundary layer control system. CFD simulation results have demonstrated a proper operation of the air intake. The mass flow requirements have been met with some margin and the total pressure recovery was observed to be within the expected figure. Furthermore, the obtained air intake operation state exhibits significant margin with respect to unstart and hence significant total pressure recovery increase possibility.
Illustrations of the internal layout of the final low speed air induction system configuration for Mach 3 operation are provided below as Fig. 7 and Fig. 8, followed by an illustration of the flow topology within the air intake duct at Mach 3 in Fig. 9:

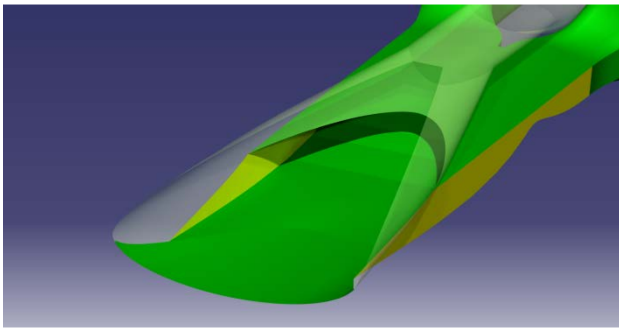

Figure 7: LAPCAT MR2 Low Speed Air Intake
Low speed air intake internal layout overhaul view with dual mode ramjet walls in transparency, low speed air intake side walls in yellow and other intake walls in green

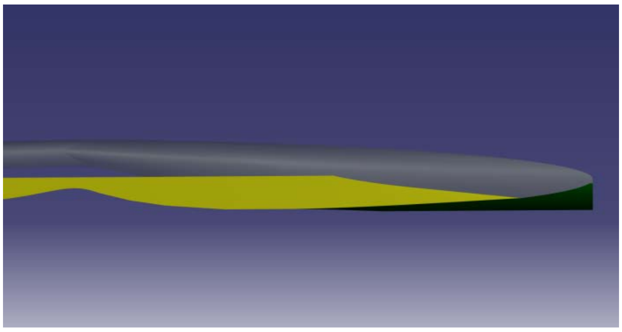

Figure 8: LAPCAT MR2 Low Speed Air Intake
Low speed air intake internal layout side view with dual mode ramjet walls in transparency, low speed air intake side walls in yellow and other intake walls in green

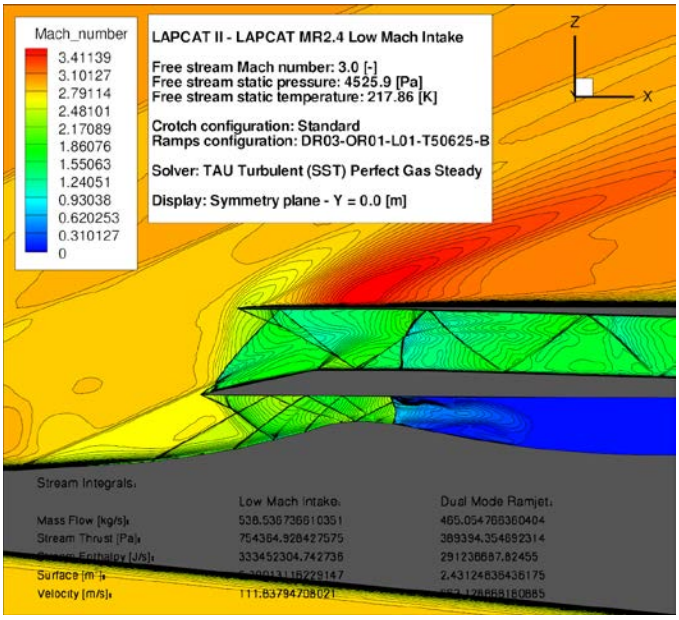

Figure 9: LAPCAT MR2 Low Speed Air Intake
Low speed air intake Mach number profile at the symmetry plane for the best performing configuration at Mach 3

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