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Development of a Free Jet test facility aiming at preliminary validating aero-propulsive balance prediction methodology for hypersonic air-breathing vehicles

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Abstract

In order to validate a trustable methodology to predict the aero-propulsive balance of an air breathing vehicle at high Mach number, MBDA developed a large scale free jet test facility allowing to test a full scale flight experimental vehicle in conditions as close as possible to those encountered in actual flight. Taking benefit of the flight vehicle capability to autonomously operate, the link between the vehicle and its support is limited to 4 piezoelectric gages allowing to directly measure the aero-propulsive balance while performing a variation of injected fuel to air ratio. Several runs have been performed in various test conditions. Test sequence and obtained test conditions for one of these runs, performed in conditions representative to Mach 6 flight, are presented. During the test, the flight vehicle operated properly while the aero-propulsive balance measurement system provided useful test data. It has been possible to measure the aero-propulsive balance along the flow axis during all the test sequence through no-combustion condition, ignition at low fuel-to-oxygen equivalence ratio and then progressively increasing fuel-to-oxygen ratio up to very rich conditions. Numerical simulations have been performed for different fuel-to-oxygen ratio by using some experimental data to define relevant boundary conditions. Such numerical simulations show a very good agreement with test data. For example, for a fuel-to-oxygen ratio equal to one, aero-propulsive balance discrepancy between simulation and test is smaller than aero-propulsive balance variation corresponding to +/- 2.5 percent of fuel-to-oxygen ratio. Such results, obtained in conditions very close to the actual flight ones, confirm the capability of numerical simulation to accurately predict the in-flight aero-propulsive balance.

Keywords: *Hypersonic aero-propulsive balance, free jet testing*

Nomenclature and definition

Aero-propulsive balance - 3axial thrust-minus-drag forces and moments

Dual-mode ramjet - ramjet operating with a subsonic internal flow at low flight Mach number (~Mach 2+) then transitioning to supersonic internal flow at higher Mach number – scramjet (~Mach 6+)

Fuel-to-oxygen ratio - mixing ratio between fuel and oxygen divided by the stoichiometric mass ratio what can be the composition of entering hot gas

FADS – Flush Air Data System

TPYROBOLT – time of on-board system start

TOUV – time of air inlet door opening

TALLUM – time of dual-mode scramjet ignition

TAIRTORCHE – time when the igniting torch is cut-off

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1. Context and objectives

Since 2000s, and under French Ministry of Defense support, MBDA and ONERA have been developing hypersonic air-breathing propulsion technology focusing on dual-mode ramjet able to autonomously accelerate from Mach 2+ to Mach 6+ and associated vehicle.

On the basis of previous studies led in 1990s, one of the key issues identified at the beginning of this technology development effort was the need to develop and validate a trustable methodology to predict aero-propulsive balance (generalized Thrust-minus-Drag balance) at high Mach number.

As a matter of fact, when flight Mach number increases, the aero-propulsive balance becomes more and more sensitive while it becomes more and more difficult to properly simulate flight conditions in ground test facilities. In that conditions in-flight aero-propulsive balance can be only predicted by numerical simulation validated by ground testing as representative as possible (configuration and flow conditions) to flight.

To reach that goal, the LEA program was consisting in developing an experimental vehicle without any technology demonstration purpose and directly insert it at right flight conditions [Ref.1 and Ref.2].

Unfortunately, external reasons led to stop the program in 2014 just before first flight.

In order to pursue the technology development despite this unpredicted event, it was decided to develop a large free jet test facility allowing to "fly" the experimental vehicle in conditions as close as possible to those encountered in actual flight.

Taking benefit of the flight vehicle capability to autonomously operate, the link between the vehicle and its support is limited to 4 piezoelectric gages systems allowing to directly measure the aero-propulsive balance while exploring a large range of injected fuel to oxygen ratio.

The test facility, designed for large scale free jet testing in the Mach number range Mach 4+ to Mach 6+, as well as the experimental system (experimental vehicle and its gaseous fuel system as well as the aero-propulsive direct measurement system) are described hereunder.

Then an example of a full scale free jet test run is detailed. After a description of test sequence and obtained test conditions, the operation of the system is described and a comparison between measured and predicted aero-propulsive balance is given and discussed.

2. Test facility

2.1. General design

The new free jet test facility is part of ramjet test center located in MBDA Bourges-Subdray test center. It has been designed to allow testing a large scale vehicle in free jet conditions (Fig 1).

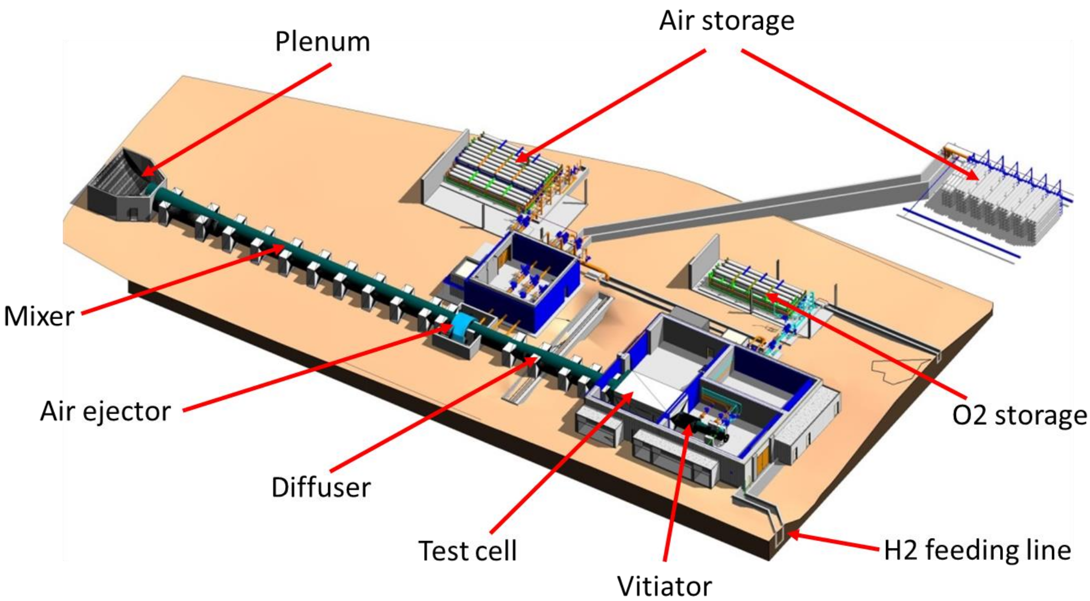


Fig 1. General view of the free jet test facility at MBDA ramjet test center

A vitiator, burning Hydrogen/Air, provides up to about 70 kg/s of hot gas to feed the supply nozzle with a maximum total temperature of about 2100K (higher total temperature is achievable but not used in operational conditions). The vitiator is equipped with co-axial three-flow injectors - Oxygen/Hydrogen/air – located in a front end and fed by dedicated plenums. The flame tube of the vitiator is cooled by the injected air (Fig 2).

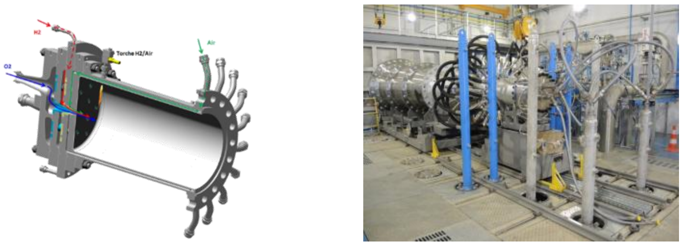


Fig 2. General concept and picture of the vitiator

The supply nozzle has an exit diameter of 1,500 mm. It is constituted by several sections: an interchangeable water cooled throat giving the Mach number (from Mach 6 to Mach 6+), a first uncooled diverging part protected by zirconia oxide coating, a series of uncooled diverging part outside the test-cell, a final section embedded in the test-cell with a removable upper part to allow integrating a mock-up partially immerged into the supplying nozzle to take benefit of the complete Mach rhombus (Fig 3).

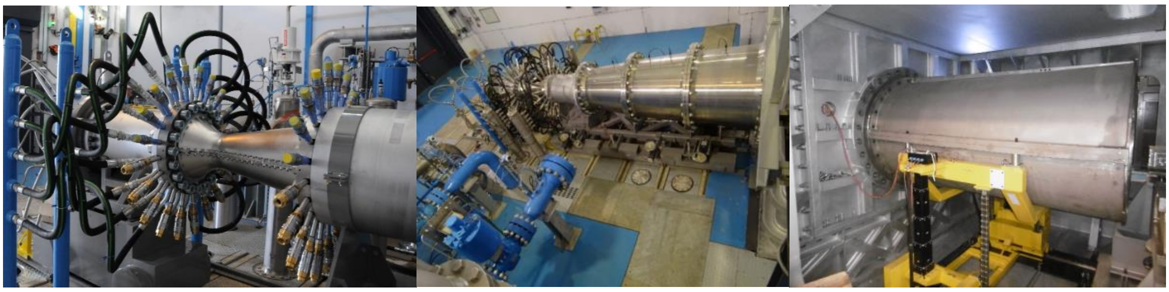


Fig 3. Supplying nozzle

For lower Mach numbers (typically Mach 4.5), a dilution section can be added between vitiator and supplying nozzle to mix hot gas exiting the vitiator with fresh air to get about 120 kg/s of hot gas at needed total temperature.

The test-cell is 4 x 4 X 8 m^3. The test line can be accessed through lateral doors but the mock-up is integrated from the top after test-cell upper wall removal (Fig 4).

Fig 4. Test cell

The diffuser catch is 2,000mm in diameter. A long diffuser with a slightly converging section is driving the main flow to a circular ejector providing up to 500 kg/s of cold air to suck the main flow. Finally, a mixing section lead to a large plenum which redirect the flow vertically. The total length of the extracting system is about 80m (Fig 5).

nota bene: A dedicated action is under progress to accurately know the characteristics of the flow exiting the supplying nozzle (Ref. 3).

Fig 5. Extracting system

2.2. Similarity rules

Using a vitiator to get the right total temperature induces a sensible change in chemical content of hot gas mainly characterised by a relatively important water vapor content and a depletion of oxygen available for the combustion into the scramjet combustor. The level of oxygen replenishment can be adapted to different similarity rules aiming to make the ground testing as representative as possible to the actual flight.

At high Mach number, the combustion process in a large scale sramjet combustion chamber is mainly driven by the mixing process and, in a certain extent, the chemical kinetics, which is directly impacted by vitiation, is not so key as for lower Mach number as the reaction time becomes enough short. At contrary, it is important to take into account the increase of hot gas heat capacity due to water vapor content (proportion of water vapor content increasing quickly while total temperature increases beyond 1500K).

It is relatively easy to define pertinent similarity rules when performing direct connected pipe test of a combustion chamber. But, when ensuring the right conditions at the entrance of the scramjet combustion chamber, it becomes very difficult to ensure at the same time representative conditions upstream the mock-up fore-body and air inlet.

Fortunately, the test facility allows adjusting independently respective air, hydrogen and oxygen mass flow rates giving the possibility to test different similarity rules and better estimate the relative importance of the different physical phenomenon acting on the aero-propulsive balance.

Moreover, at high Mach number, the goal of ground testing is not to provide direct measurement of in-flight performance but to confirm that numerical simulation is able to accurately determine such in-flight performance by validating them in test conditions as close to those of actual flight as possible: aero-propulsive performance model being only based on numerical simulation.

3. Mock-up

3.1. Flight vehicle

The LEA vehicle was initially designed to perform flight testing aiming at getting a direct measurement of the aero-propulsive balance at high flight Mach number in order to validate a dedicated methodology for the development of an air-breathing high speed vehicle and for the prediction of its performance [Ref.1 and Ref.2](Fig 6).

Fig 6. LEA vehicle and its Interface & Separation System

The LEA vehicle, 4.1m long, was actually an experimental vehicle dedicated to methodology purpose and was not aiming at demonstrating any technology related to scramjet. Then, its design was as simple as possible to limit the cost of development:

- The vehicle was accelerated to the Mach number of interest by a booster system ensuring that valuable test data will be acquired what could be the actual self-acceleration capability of the vehicle.
- The vehicle was not recoverable and, then, not reusable and all on-board data were transmitted to ground by a telemetry system.
- The vehicle was uncontrolled. The aerodynamic shape of the vehicle was designed to ensure a good stability in yaw and roll at any flight conditions. The vehicle was also stable in pitching plan when dual-mode ramjet was operating but was unstable when dual-mode ramjet cut-off ensuring a shortage of the trajectory after the scramjet cut off (but inducing the need to surely ignite the ramjet during the separation phase).
- The dual-mode ramjet was a fixed geometry one representing the configuration of a dual-mode ramjet using a translating cowl and able to operate from Mach 2+ to Mach 6+ at the vehicle injection Mach number (Fig 7).
- Limited duration of the free flight allowing to use stainless steel structure protected by a sprayed silicon based thermal insulation for the airframe and a heat sink stainless steel structure protected by zirconia oxide coating for the fixed geometry scramjet.
- The scramjet was fed with a mixture of gaseous Hydrogen and Methane ensuring a sufficient fuel density to get about ten seconds of scramjet operation. Fuel is stored in high pressure vessel (300 bars) as well as air used for igniting torch and air used for opening the air inlet door.
- The mass flow rates of Hydrogen and Methane control system was a simple open loop only driven by the Pitot pressure measured by the Flush Air Data System (FADS) installed on vehicle nose. But, in the same time, the feeding lines were equipped with accurate Venturi mass flow rate measurement systems.
- Pneumatic driven rotating air inlet door protecting the scramjet during acceleration phase and ensuring non-self-starting air inlet starting.

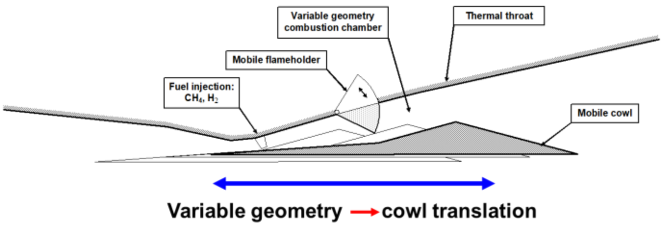


Fig 7. Translating cowl dual-mode ramjet

For the flight testing, the vehicle on-board control system was designed:

- To start a self-checking upon the receiving of a "switch-on" electrical signal from the booster system and then return an "OK" signal
- To autonomously operate upon the receiving of a "separation" electrical signal from the booster system.

Then, for the on-ground free jet testing, no modification was needed on the control system:

- The "switch-on" signal and corresponding "OK" return signal allowed checking everything was ready on-board the vehicle, including all the instrumentation.
- The "pyrobolt" signal allowed to start the on-board test sequence when the test facility had reach the right test conditions.

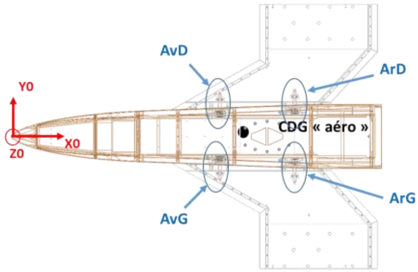
Then, only two optical fibres coming from the test facility were needed to trigger the on-board test sequence and collect all test data provided from the vehicle and its weighing system.

Nota bene: for the free jet testing, vehicle wings were removed to limit the obstruction.

3.2. Aero-propulsive balance measurement system

The vehicle is maintained in the test section by two lateral supporting struts in a fixed angle of attack, representative to actual flight. Using a fixed position system ensures the best stiffness of the system and then the minimum displacement of the mock-up during the test run (but leads to a sub-optimum position of the mock-up to ensure a full test line starting).

The link between the mock-up and supporting struts is made through four 3axis piezoelectric gages mounted on knee-joints located inside the mock-up. The knee-joints seatings have been machined during the same machining operation in order to get the maximum accuracy and avoid any mechanical blockage. The two upstream knee-joints are fixed (only a translation along Yaxis is allowed) while the two downstream knee-joints are free to translate along both X and Y axis) (Fig 8).



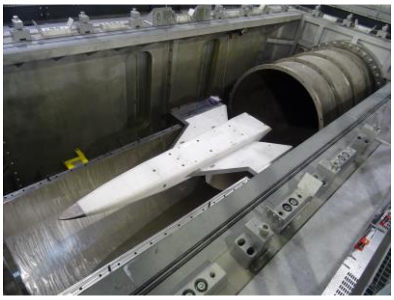


Fig 8. Mock-up mounting and Piezoelectric gages location

A dedicated tool (in yellow on Fig 9) is used to integrate and test the mock-up prior to its transportation to the test facility and its installation into the test section.

Fig 9. Mock-up and its handling tool (yellow part) on integration pad (in grey)

As shown on Fig 10, some efforts can be introduced in X and Z axis generating moment around Y axis too. These forces are measured by dedicated piezoelectric cells. Then the measured response of the piezoelectric cells embedded into the mock-up allows calibrating the weighing system.

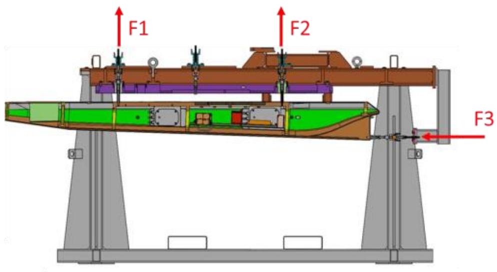


Fig 10. Weighing system calibration

Initially, it was intended to perform a lot of calibration measurement with a lot of efforts and moment combination. But, the weighing system exhibited a very good decoupling between its axis and, after cross talk correction, the data measured by the piezoelectric cells are directly used to determine forces along X and Z axis and moment around Y axis. The accuracy was globally estimated better than +/- 35N. By another way, the system showed a good repeatability and a good robustness against high loading due to starting and unstarting of the flow in the test facility.

4. Test sequence

The general test sequence is as follows (Fig 11):

- The extracting system empties the test cell while a limited air mass flow is injected in the vitiator to prevent supply lines depressurization.
- Oxygen mass flow is then progressively increased to reach about 20% of its nominal value.
- Hydrogen flow is started and, during its ramp-up toward 30% of its nominal value, the vitiator

is ignited thanks to a H2/Air torch.

- After a few seconds allowing confirming vitiator ignition (devastating late high pressure ignition avoidance), all mass flows are ramping-up to their nominal values.
- When nominal operation conditions are obtained, the mock-up test sequence is initiated by the "separation" signal provided by the test facility control system.
- At the end of the test sequence, the vitiator is turn off and the mock-up fuel system is purged into remaining air flow.
- When fuel system purging is completed, the extracting system is turn off.

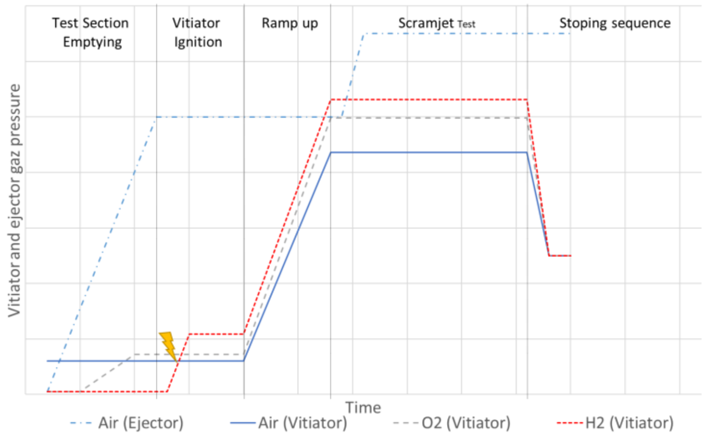


Fig 11. Test sequence

As said previously, different combination of different respective air, oxygen and hydrogen flow parameters have been tested to explore the effect of different similarity rules.

When the test section is empty, a so-called Full Starting Mode of the test line is easily obtained where the ejector system is working in supersonic mode (Fig 12). However, when a large mock-up is in place in the test section, the corresponding obstruction and pressure drop prevent to fully start the test line and the so-called Partial Starting Mode occurs corresponding to a chocked diffuser section with ejectors working in a saturated supersonic mode. In extreme case, this Partial Starting Mode can result in a higher pressure inside the test cell and consequently a flow separation at the end of the supplying nozzle which amplitude is directly dependent of imposed test conditions (Fig.12).

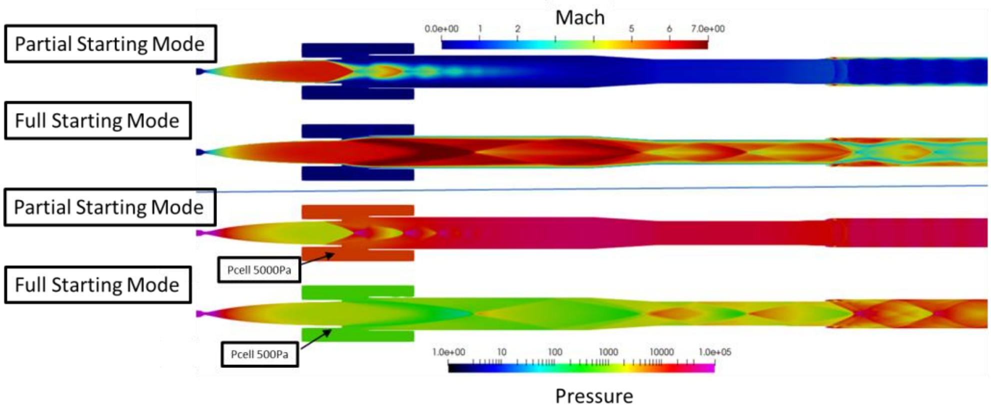


Fig 12. Full/Partial Starting Modes

In order to limit the effects of the Partial Starting Mode, while keeping the size of the test facility "reasonable", extracting system and Vitiator settings have been optimized to maximize the Mach rhombus size by maximizing vitiator total pressure up to 40bar (through Mass Flow Rate) and setting the optimal Vitiator/Ejectors Mass Flow Rate Ratio (considering the saturated supersonic mode).

5. Typical test run and qualitative results

Let's consider here one of the performed test run. Corresponding test conditions are the following:

Table 1. Test conditions

Q vitiator	68.5 kg/s
Ti vitiator	1670 K
Pi vitiator	36.8 bar
P dynamic	42,280 Pa

5.1. Test sequence

After reaching the nominal test conditions, the on-board test sequence of the mock-up is triggered by the "pyrobolt" signal sent from the test facility control system. The sequence is as follows:

- Opening order for the air inlet door (TOUV)
- Opening order for high pressure CH4/H2, H2 and air bottles
- End of air inlet opening
- Injection ports fully fed
- Ramjet ignition at relatively low fuel-to-oxygen (TALLUM)
- Torch cut-off (TAIRTORCHE)
- Ramjet fuel-to-oxygen ramp-up
- Ramjet cut-off

After air inlet door, injection must be quickly fed by gaseous fuel as there are cooled by the fuel and cannot withstand high temperature without cooling more than 1 to 2s.

The ramjet is ignited at relatively low fuel-to-oxygen ratio. During that phase, some injection struts are supplied with pure hydrogen in order to ensure a robust ignition. Then, the injection transitions to 100% CH4/H2 mixture and the fuel-to-oxygen ratio starts to progressively increase.

When approaching fuel-to-oxygen ratio One, the fuel-to-oxygen ratio ramp-up more rapidly up to reach 1.3 in order to get a partial blockage of the air inlet (flow detachment on the last compression ramp).

As previously said, the test line is operating in Partial Starting Mode and the upper surface of the mock-up after-body is partially outside the Mach number rhombus as shown on Fig 13.a. Then, after ramjet ignition, the counter-pressure – and consequently the test cell pressure increases (Fig 14) and reinforces the interaction between Mach number rhombus and the upper surface of the mock-up after-body while the test Mach number is slightly decreasing (Fig 13.b).

a – ramjet fuel-to-oxygen ratio = 0 b – maximum ramjet fuel-to-oxygen ratio

Fig 13. Mach number rhombus/Mock-up interaction during test run

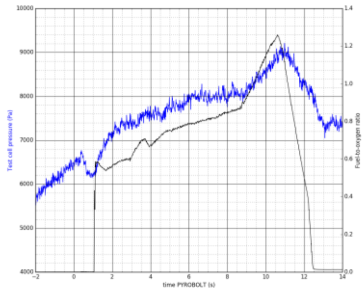


Fig 14. Evolution of test cell pressure with fuel-to-oxygen ratio

5.2. FADS measurement

The Flush Air Data System has been designed and calibrated to accurately measure Pitot pressure, Mach number, angle-of-attack and side-slip angles (+/-0.1°).

In following figures, the time origin is the beginning of the mock-up test sequence. The ramjet operates about 10s.

As shown on Fig 15, the test line starting and unstarting phases are very disturbed. During that time the weighing system records normal effort 2.5 times higher that nominal one. But, when the starting shock has passed the mock-up, well stable conditions are obtained during all the mock-up test sequence (Fig 15 and Fig 16). Nevertheless, the angle-of-attack is slightly increasing with fuel-to-oxygen ratio because of the reinforced interaction between Mach number rhombus and upper surface of the after-body creating an additional pitching moment on after-body upper surface (Fig 17).

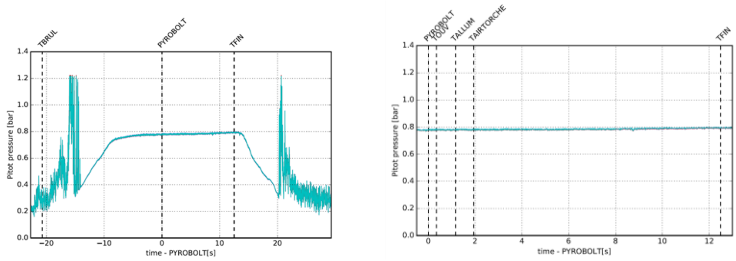


Fig 15. Pitot pressure as function of time and zoom during ramjet operation (uncertainty +/-300Pa)

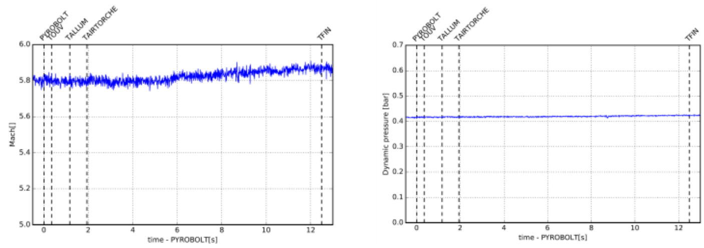


Fig 16. Mach number and dynamic pressure during ramjet operation

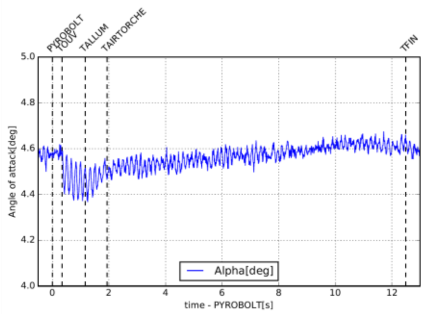


Fig 17. Angle of Attack during ramjet operation

5.3. Fuel system operation

The fuel system operated properly and, thanks to the self-adaptation to the measured Pitot pressure, the realized fuel-to-oxygen ratio evolution is in good compliance with the targeted one except 0.5s delay (Fig 14).

5.4. Ramjet operation

After ignition and transition to 100% CH4/H2 mixture injection, the ramjet operates properly up to and beyond fuel-to-oxygen ratio one. Then a partial blockage of the air inlet occurs and leads to an overpressure on the last compression ramp but without fully unstarting the air inlet (see Fig 18).

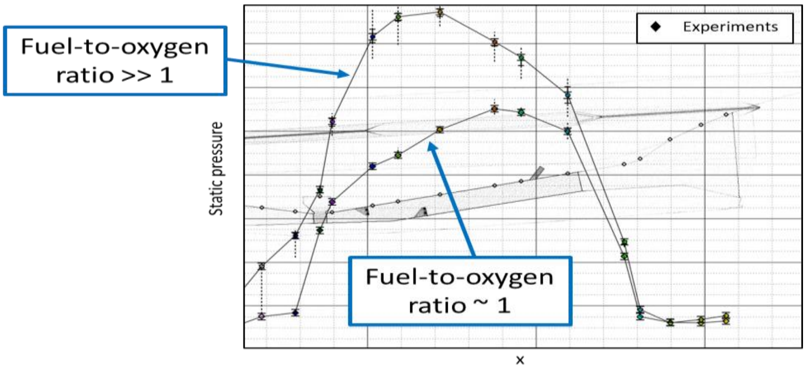


Fig 18. Evolution of average pressure along the ramjet system as function of fuel-to-oxygen ratio

5.5. Measured aero-propulsive balance

As shown on Fig 19, the interaction between Mach number rhombus and after-body essentially affects the upper part of the supplying nozzle and the upper surface of the mock-up. Then, the aero-propulsive balance component on X axis can be pertinently analysed as it mainly depends on the upstream Mach number which is slightly sensitive to the test cell pressure.

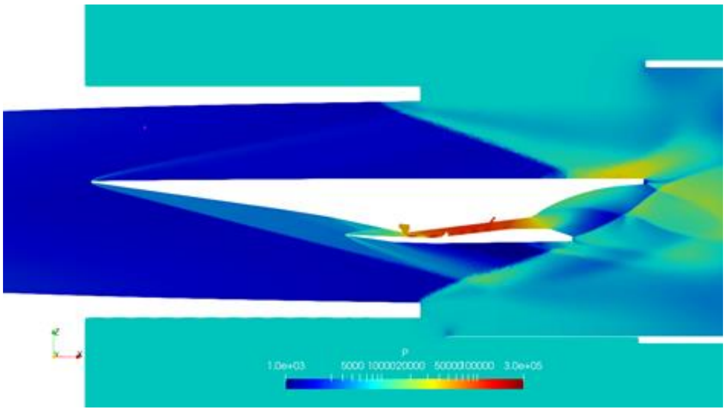


Fig 19. Flow path around the mock-up

The aero-propulsive balance measured all along the test run is shown on Fig 20.

Nota bene: the choice of reference axis (see Fig 8) makes that a negative aero-propulsive balance correspond to an acceleration of the vehicle.

First one can see a good return to zero at the end of the run despite the very harsh environment during the run. After stabilisation of test conditions, the air inlet opening reduces slightly the drag. At scramjet ignition at intermediate fuel-to-oxygen ratio, the aero-propulsive balance goes zero and then continuously increases up to the maximum fuel-to-oxygen ratio. After scramjet cut-off, the aero-propulsive balance comes back to its initial level after air inlet opening.

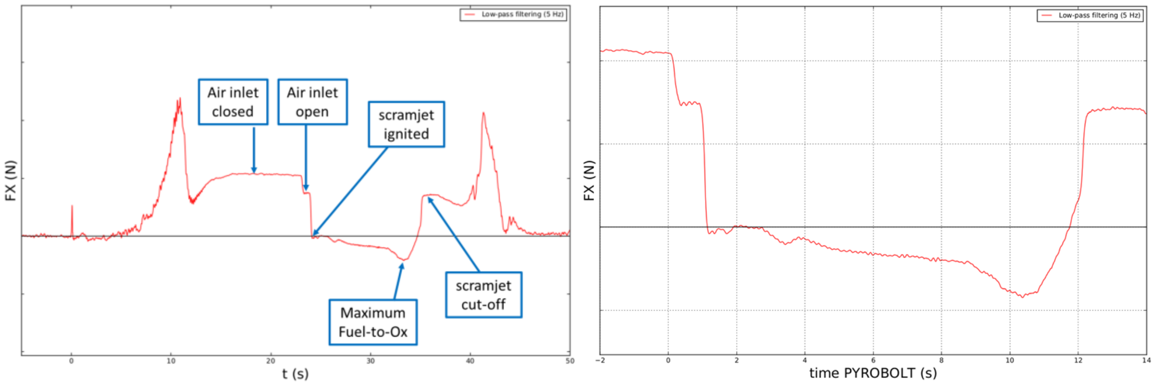


Fig 20. Aero-propulsive balance as function of time and zoom on scramjet operation

6. Numerical simulations

6.1. Simulation tool characteristics

URANS CFD computations are performed with ONERA's CEDRE Software [Ref. 4] in order to compare internal and external flow path, wall static pressures and aero-propulsive balance with the experimental data. The computational domain extends from the facility nozzle inlet (dark red on Fig 21) to the diffuser catch (dark blue on the same figure). Computations are performed by blocks, following the "Nose-to-Tail" approach [Ref. 5]. A first $k - \omega\ SST$ computation gives the combustor supersonic inlet condition. The vitiator exit temperature and composition are estimated through H_2/Air equilibrium computations, correlated with measured vitiator pressure and heat losses.

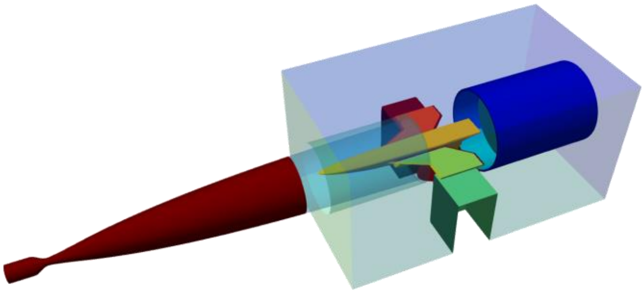


Fig 21. Computational domain

Reactive computations are then made from the combustor inlet to the combustor internal nozzle outlet for the fuel-to-oxygen ratios of interest. They are based on a tried-and-tested methodology [Ref. 5, Ref. 6, Ref. 7] with a $k - \omega\ SST$ turbulence modeling and Davidenko finite-rate chemistry approach to deal with the CH_4/H_2 combustion [Ref. 8]. These URANS computations are performed with a 1 µs time-step and a first order implicit numerical scheme. Inviscid fluxes are computed using the HLLC approximate Riemann solver, second-order spatial accuracy and Van Leer limiters. Estimated facility and mock-up wall temperatures are imposed with isothermal walls in the computations. The boundary conditions of the first computation are then adjusted in a final computation by imposing the combustor computation outlets.

6.2. Simulation methodology

The partially started state of the facility can finally be approximately simulated with two methodologies. The first one consists in turning the actual test-cell walls as subsonic inlet conditions, and imposing the test-cell pressure measured during the test. It results in a low mass flow rate inflow of vitiated air in the tunnel. The test-cell exit boundary condition (diffuser catch) is specified as a supersonic outlet and remains stable despite the partially supersonic flow flowing through. The second approach allowing to reproduce the partially started flow in the test-cell uses a larger computational domain that extends to the upstream ejector station (Fig. 12). The experimental static wall pressure measured at this position is imposed with a subsonic outlet condition. Thanks to a slight wall temperature adjustment and with walls numerically considered as such, the computed test-cell pressure is consistent with the experimental one. Both methods give a decent insight of the test-cell flow field topology (illustrated on

Fig 22) and may be pragmatically used to compare aero-propulsive balance.

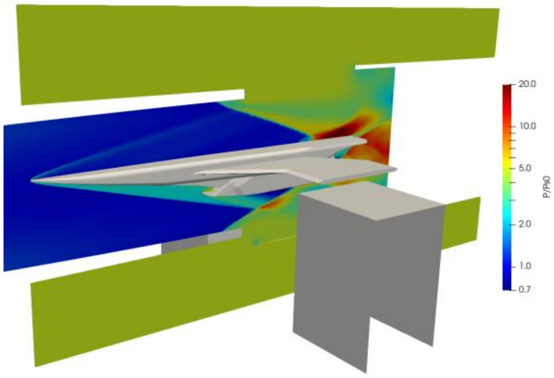


Fig 22. Static pressure field for the ER1 case (divided by rhombus static pressure) – 1st approach

7. Comparison numerical simulation/test data

7.1. Ramjet operation

Fig 23 shows a comparison between numerical simulation and test results related to the evolution of average static pressure along the ramjet system at a fuel-to-oxygen ratio close to 1. The wall pressures on the air inlet external ramps are consistent with the computations made for the estimated test conditions and vehicle positioning. Combustor internal flowpath wall pressures estimated by numerical simulation are in good agreement with test data. The description of the flow field within the combustor with the described methodology is thus quite satisfactory.

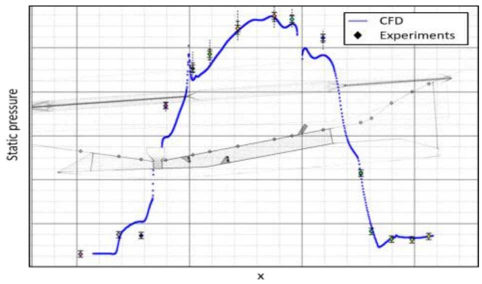


Fig 23. Average pressure along the ramjet system at fuel-to-oxygen ratio close to 1 comparison test results/numerical simulation

7.2. Aero-propulsive balance

Fig. 24 gives an example of how numerical simulation results compares with test data regarding the aero-propulsive balance. For a fuel-to-oxygen ratio close to One, the numerical simulation prediction is very close to the measured aero-propulsive balance. The discrepancy between computation and test is largely smaller than the difference of aero-propulsive balance calculated with +/- 0.025 of fuel-to-oxygen ratio corresponding to a variation of +/- 60 N.

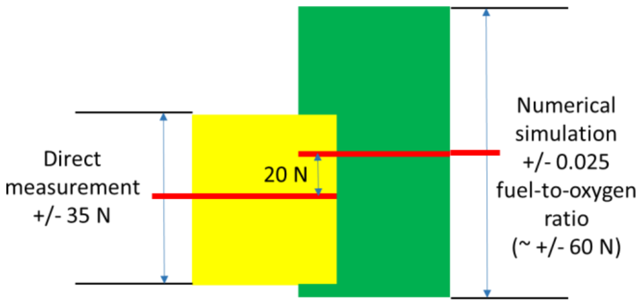


Fig 24. Comparison numerical simulation / Test data for fuel-to-oxygen ratio close to One

8. Conclusion

In the frame of its technology development program related to hypersonic airbreathing systems, MBDA France developed a large scale free jet test facility. The first purpose of this test facility was to replace the LEA flight testing which was initially planned to demonstrate the capability to predict, on ground and mainly by numerical simulation, the flight performance of a hypersonic airbreathing vehicle.

The performed test series allow verifying that the vehicle on-board system works properly and demonstrating that the vehicle was ready to fly if any new opportunity of flight testing would appear.

Moreover, it has been possible to get valuable direct measures of aero-propulsive balance showing positive thrust-minus-drag values as soon as the dual-mode ramjet is ignited.

Despite the very complex flow structure linked with the partial starting operation mode of the test line, numerical simulation has been successfully performed and comparison between test data and numerical simulation results showed a very good agreement.

These results demonstrate the possibility to develop an aero-propulsive performance model fully and solely based on numerical simulation enough accurate to ensure the success of future operational products developments.

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