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The VINCI® upper stage engine: toward the demonstration of maturity

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ABSTRACT

The intent of this publication is to provide an overview of the progress of the VINCI development over the 2012-2013 period.

The VINCI is a cryogenic expander cycle engine combining the required features of this cycle, i.e. high performance chamber cooling and high performance hydrogen turbo-pump, with proven design concepts based on the accumulated experience from previous European cryogenic engines such as the HM7 and the Vulcain. The Vinci engine is the reference cryogenic upper stage engine for the future European Launchers. Additionally, the high performance of this engine and its restart capability offer potential applications on various future launcher upper stages as well as orbital spacecrafts.

The current phase of the VINCI development is focused on confirming the system design maturity through additional engine test campaigns with the M4 and M5 engines.

In 2012 and 2013, the M4 engine test campaign is implemented with the objective to test the engine improvements necessary to comply with the requirements of the new A5ME launcher and to prepare the extensive test program to be performed in a second phase of development aiming at qualifying the engine for flight.

Figure 1 : The VINCI® engine at P4.1 test bench.

Introduction

The VINCI® engine is a 180 kN re-startable upper stage cryogenic engine. Its preliminary design was initiated in the frame of the Ariane 5+ program managed by CNES under delegation of ESA. Between 2006 and 2008, its engineering and testing were conducted under the ESA Future Launcher Preparatory Program (FLPP). VINCI® is currently the basis for the next evolution of the ARIANE 5 launcher developed by Astrium as launcher prime contractor in the frame of ESA A5 Mid life Evolution (A5ME) program. VINCI® is also dedicated to ARIANE 6 upper stage.

The VINCI® is a cryogenic expander cycle engine. This cycle was found to be the most promising option to achieve the overall objectives of higher reliability, higher performance, multiple ignition capability and low recurring cost.

The engine overall system design and integration is under responsibility of Snecma (Safran). The major subsystem contractors are ASTRIUM GmbH (Ottobrunn, Germany) for the thrust chamber, GKN (Trollhättan, Sweden) for the turbines of the turbopumps, AVIO (Turin, Italy) for the oxygen turbopump, Snecma for the hydrogen turbopump, Safran-Herakles (Bordeaux, France) for the composite nozzle and. Techspace Aero (Liège, Belgium) for the valves. The engine hot fire testing is performed at DLR P4.1 test facility (Lampoldshausen, Germany) and Snecma PF52 test facility under modification.

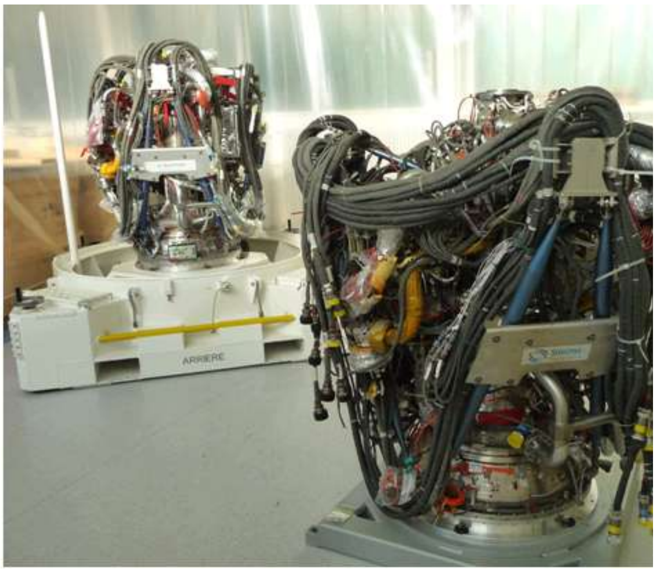

Figure 2 : View of M3 and M4 engines

Engine architecture and specification

The engine is characterized by a high performance hydrogen turbopump, an optimized combustion chamber cooling circuit, the use of advanced manufacturing processes (powder metallurgy impellers, cooling channel high speed milling) and a constant use of a design to cost approach.

The engine architecture, which was already presented in numerous previous publications (see references 1, 4 and 5) is designed to meet the goal of reliability, simplicity and low recurring cost. The engine flow schematic is shown on figure 3.

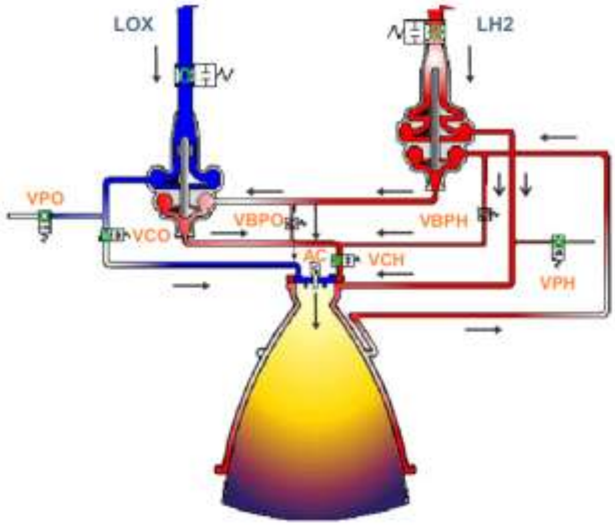

Figure 3 : VINCI flow schematic

The combustion chamber body is a "smooth wall" chamber using the same technology as the HM7B® and VULCAIN®, but significantly longer in order to meet the thermodynamic performance needed by the expander cycle. The use of a regenerative nozzle extension was avoided in order to reduce cost and number of fluid interfaces.

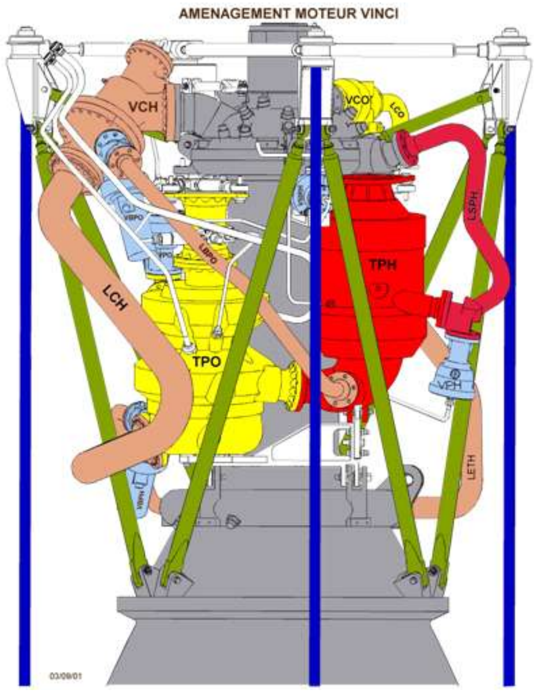

Figure 4: VINCI mechanical arrangement

The engine has two separate turbopumps mounted close to one another in a "power pack" kit as shown on figure 4. Turbines are set "in serial", and a set of two by-pass valves adjusts their flow rates. This set allows to tune the engine operating point, in terms of thrust and mixture ratio.

Both turbopumps have integral inducers, which lead to low NPSP with the objective to avoid the use of boost pump.

A H2/O2 gas fed torch, electrically initiated by a spark system, is used for engine ignition. This igniter is fed by gaseous oxygen and hydrogen contained in high-pressure bottles operating in a blow down mode. The igniter is developed by APP (Netherlands) under contract from ASTRIUM GmbH. Starting with engine M5, a dual spark plug ignition system is implemented to ensure complete redundancy of the system.

The oxygen chamber valve is a pneumatic ball valve. This choice is based on the priority given to simplicity of architecture and low recurring cost. The fuel chamber valve (VCH) is a pneumatic poppet valve.

The low recurring cost objective has led to the choice of slow actuation rate by-pass valves. The large multiplication rate between actuation electric motor and valve shaft ensures stability of the valve, therefore eliminating the need for an electronic control.
The engine has a set of poppet chill-down valves with calibrated orifices, which are sized in order to allow a sufficient discharge flow during start-up and shutdown transients.

One of the major new features of the engine is a large area ratio deployable composite nozzle. The nozzle, shown on figure 5, comprises a fixed part attached to the combustion chamber and a deployable part stored around the upper part of the engine during the first stage flight.

The nozzle deployment system is designed by Kongsberg (Norway).
One major axis of the current development period is the confirmation of the re-start capability. This function leads to place a strong focus on the thermal control of the engine and the thermodynamic conditions of the propellant at engine inlet.

Figure 5 : VINCI® Nozzle Extension after testing

Summary of the engine system engineering

Over the 2011 – 2012 period, taking into account the experience gained through the first three engine campaigns from M1 to M3 and incorporating the requirements originating from the A5ME launch vehicle and its new upper stage, the mode of operation of the engine was optimized and consequently the engine technical specification and the sub-system specifications were updated .
At full thrust, the VINCI® is designed to operate in a domain centered around a nominal thrust equal to 180 KN and a mixture range MR=5.7 / 6.2. It is also designed to operate at a low thrust level equal to 130 KN. This dual operating mode was selected in order to optimize performance. In a reference mission, the first main boost is performed in two successive steps of 180 KN first, then 130 KN. The subsequent re-start boosts are performed at 130 KN.
A Complementary Preliminary Design review was organised in November 2010 to confirm the assumption taken as the basis of the present phase of development. Subsequent engineering key points in 2011 confirmed the dual thrust level operation.
The engine critical design review is planned at the end of 2014 after completion of the sub-system critical design reviews in the first half of 2014. The purpose of these latter reviews is to freeze the configuration of the qualification engine.
In conjunction with the engine development, the propulsive system functions such as propellant feed, tank pressurization, helium command system are developed by Snecma with the goal of ensuring optimized interfaces between the engine and the propulsive system.

Figure 6 : Vinci engine M5 during dynamic testing

Environmental test

A series of environmental dynamic tests were performed during the first quarter of 2013. They were performed at IABG Dynamical Test Facilities (Germany).They consist of a series of low level sine, high level sine and random excitation performed on a complete engine with a shaking table. The dynamic tests are performed with the lower part of the nozzle both in a stowed and deployed configuration. Nozzle deployment tests were performed before and after the dynamic tests. Engine M5 that will be fire tested afterward was used for these tests. M5 is shown been prepared for dynamic tests on figure 6.

Sub-system tests

A series of tests of an improved dynamic seal package (DSP) for the oxygen turbo-pump are on-going at AVIO dedicated test facility in Turin. These modifications aim at improving reliability while reducing the leakage flow. They are based on the use of an improved slinger, improved floating ring and use of segmented radial seals.

The engine firing test facilities

The engine hot-firing tests are performed on the P4.1 test stand at DLR in Lampoldshausen, Germany.

The P4.1 is a versatile test bench offering the capability of testing the engine at ambient pressure or in vacuum conditions, without the nozzle, with the fixed part of the nozzle or with the fully deployed nozzle. The engine can be operated in full vacuum conditions during the whole duration of a test.
The P4.1 is equipped with a thrust measurement load cell. Its characteristics make it the primary tool to study transient robustness and restart conditions.
The bench propellant feed-lines closely approximate the impedance of real upper stage lines through the use of a buffer tank during the start-up transient on both the hydrogen and oxygen side.
The chill-down line flow resistance and downstream pressure boundary conditions are also representative of real stage lines.
Figure 7 shows a view of the test cell and exhaust duct. During the operation of the engine, vacuum (approximately 10 mbar) is maintained using steam ejectors.

Figure 7 : View of the engine in the P4.1 test cell

Over the 2012-2013 period, the design of the future test cell devoted to production acceptance tests started at the PF52 test bench located at Snecma in Vernon, close to the assembly hall. The goal is to reduce the duration of the acceptance process without compromising the quality of the engine tuning and the contribution to reliability brought by the acceptance test. A Critical Design Review of the test cell design was held in September 2012. The PF52 will operate at ambient pressure, except during the start-up process during which it will operate at vacuum condition. This bench will be used for last development test campaigns and qualified with the engine to allow efficient acceptance tests in the production phase.

Engine first three test campaigns

From 2005 to 2008, two engines were tested, M1, M2 and their refurbishment. After changes of components, M1 was refurbished into M1B and M1C; M2 was refurbished into M2R.

The main objectives of the M1C and M2R test campaigns were:

- to demonstrate the restart capability of the engine,
- to accumulate testing time and number of firings at various operating points of the flight domain,
- to confirm the robustness of the start-up and shut-down transients,
- to test various types of chill down.

The M3 test campaign took place over the last semester of 2010 and the first quarter of 2011.
Performing tests with the fully deployed nozzle was one of the highlight of the M3 test campaign.
Operation at a higher and much lower thrust than nominal was also a major achievement of the campaign. Steady state operation at 206 KN (compared to the 180 KN nominal) was achieved with the hydrogen turbopump rotating speed and exit pressure reaching 103000 rpm, 300 bar.
Throttling at very low thrust level was successfully performed with successive operation at 100 KN, 61 KN, 43 KN, 27 KN (see figure 8). This result is essential to demonstrate the capability of the engine to fulfil multiple versatile missions which include re-boosts at a reduced thrust level.

A very long duration test with a single firing of 714 s, compared to the maximal 740s for a mission into geo-stationary transfer orbit, was also performed.
Post test examination performed on engines M1C, M2R, M3 did not show evidence of life related damage. It showed an excellent behavior of the chamber hot gaz wall of the chamber liner, a usually critical component for rocket engine. The behavior of the chamber was documented in a AIAA 2012 publication.
The M3 test campaign was the longest one with a total of 6287 s cumulated duration and 13 ignitions.

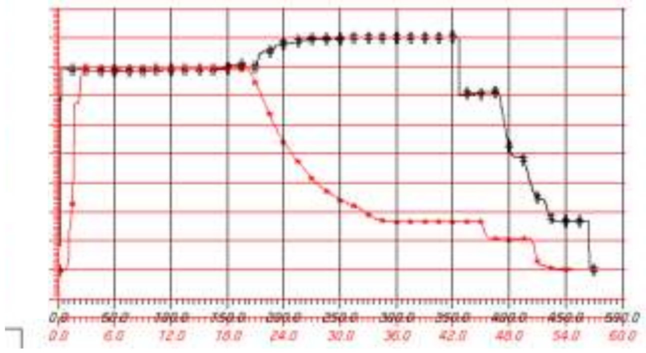

Figure 8 : Power level during two successive boost with the objective of operating at very low thrust (down to 15% of nominal thrust)

Figure 9 : View of the engine in operation with the fixed part of the nozzle

<u>M4 and M4R test campaigns</u>

The M4 test campaign took place in 2011. The M4R campaign took place in 2012. Their main objectives were the following:

- To maturate the engine definition by incorporating modifications aimed at improving the subsystem robustness
- To consolidate the knowledge of the engine operation at full and reduced thrust level (especially 130 kN level)
- To incorporate modification with the goal of obtaining an easier and faster engine production

A modified hydrogen turbo-pump with improved performance was introduced on M4.
M4 was refurbished as M4R with an improved dynamic seal package for the oxygen turbo-pump.
M4 was equipped with a functional nozzle deployment system that allowed nozzle deployment followed by engine start-up in a flight representative sequence. The ball screws of the nozzle deployment system nozzle were equipped with new moving nozzle support and fixed nozzle attachment more tolerant to the nozzle thermal flux in operation.
M4 was also equipped with a set of new solenoid valves re-designed with the goal of improving robustness.

With the M4 Engine, an additional effort to optimize the production process for components, sub-systems and Engine assembly was introduced in order to further reduce the production cycle and cost. The following areas of activity can be mentioned:

- During engine integration, an effort to make the engine more tolerant to interface geometrical scatter and easier to assemble
- Prior to test (and prior to flight in the future) an effort to reduce the lead time of engine integration to the test bench (or to the stage)

Most of the tests of the M4-M4R campaigns were multiple boost tests. One of M4R tests was a 3 firing test. This test simulated a nominal flight comprising of a first 230 sec boost , followed by a 120 sec boost , and a 5 sec re-start third boost. The thrust was varied during the first boost within the flight domain, below and above the nominal value (180 KN).

One of the major objectives of M4-M4R campaigns was the demonstration of margins with respect to cavitation for both propellants. Low inlet pressure starts were performed. The tolerance of the engine to the inlet thermodynamic conditions, i.e. sub cooled oxygen and two phase flow which can occur at the beginning of a re-start boost was also extensively demonstrated. For example, multiple ignitions and long duration operation (420s max) were successfully performed on M4R with 80K sub-cooled LOX at pump inlet, confirming VINCI robustness in those conditions .

Two tests with operation of the engine in idle mode were performed successfully on the M4R campaign. They consist in operating the engine with the rotation of the turbines being blocked. The engine operates at a low chamber pressure , approximately 1 bar and deliver a small thrust (2.4 KN). A 63 sec. test and 180 sec. test were performed in idle mode, without hardware damage (see M4R-06 on figure 10). The idle mode operation offers potential benefit for stage de-orbitation since it requires simpler stage re-conditioning prior to engine firing.

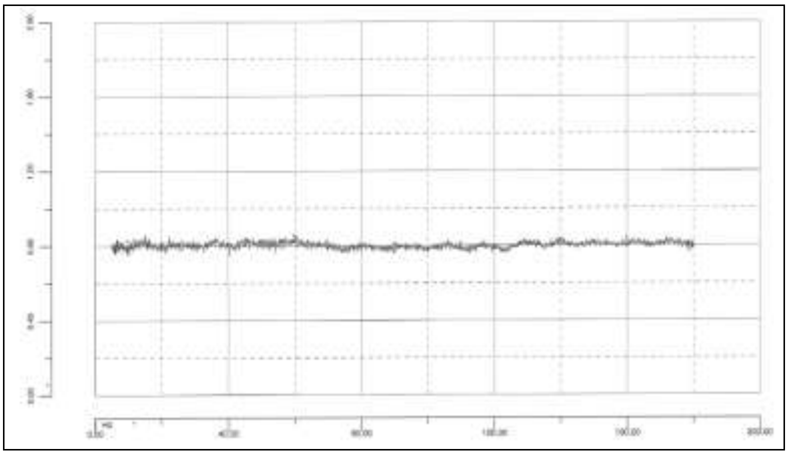

Figure 11: Stable VINCI Chamber Pressure during idle mode tests M4R-06.

The M4 and M4R campaigns also served the objective of demonstrating engine endurance with a total cumulated operating duration of 4600 sec i.e. approximately 3 design life. The design life includes the eventuality of performing two acceptance tests prior to flight.

M5 test campaign

The M5 engine came out of final assembly during the first quarter of 2013. Prior to being fire tested, it was be submitted to extensive dynamic testing using a shaking table with sine and random acceleration excitation. The dynamic tests are performed with the nozzle in both a stowed and deployed configurations.

M5 incorporates additional modifications to further improve the engine reliability and the design robustness such as a fully redundant ignition system with dual spark plugs. Similarly to M4, M5 incorporates modifications introduced with the goal of simplifying engine manufacturing and engine preparation. One example is the design of the fluid circuit between the exit of the fuel turbopump and the inlet of the regenerative circuit. The branching toward the purge/exhaust line and the regenerative circuit upstream filter were merged in a single part made with additive manufacturing.

One of the main objectives of the M5 firing test campaign is to establish the robustness of the start-up and shut-down sequence with respect to various thermal environments which can occur when re-starting the engine.

M4 and M5 are last “development” engines before entering qualification. The results of the M4 and M5 test campaigns will be the basis of the engine Critical Design Review and will make possible finalizing the definition of the qualification engine. After completion of the M4 test campaign, the total cumulated duration of 15546 s representing 62 ignitions had been obtained.

The qualification test campaigns

M6 and M7, the first two engines of the qualification phase, will be sub-system qualification engines. They will be submitted to tests confirming margins with respect to major sub-system limitations. The two latest engines of the qualification phase, Q1 and Q2, will be qualification engines with the goal of demonstrating endurance in the flight domain.

Conclusion

The VINCI®, as a high-performance cryogenic re-ignitable upper stage engine using the expander cycle, is a key element for the future developments of European launchers.

From 2005 to 2008, the first engine test campaigns relying on engine M1, M2, M2R showed that a reference system configuration with reliable transient and steady state behavior had been obtained. They demonstrated the engine restart capability, the reproducibility of the transient behavior and initiated the endurance demonstration.

In 2010 and 2011, the M3 campaign completed this demonstration with several tests of the fully deployed nozzle, tests covering the compete flight operating domain and beyond into the extreme domain, operation at a very low thrust level showing the adaptability of the engine to multiple ARIANE 5ME mission requirement.

Over the 2012-2014 period, the M4 campaign, and latter the M5 campaign, have the goal of demonstrating the maturity of the system. When completed these test campaigns will provide the assurance that a final development phase with margin test campaigns and qualification test campaigns can confidently be initiated.
The future key milestone of the VINCI® development will be the engine Critical Design Review at the end of 2014 and the engine qualification at the end of 2016.

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