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Development of an LNG Electro-Pump for a cryogenic launcher stage

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Abstract:

Electro-pump technologies are becoming an increasingly attractive solution for high performance launcher stages due to the lower complexity and higher flexibility of electro-pumped engine cycles w.r.t. turbo-pumped classic solutions. This can be an important benefit in the frame of European development of future Expendable and Reusable Launch Vehicles (ELV/RLV). Together with the simplicity and compactness of this concept, the constant improvement of battery technologies could pave the way for an efficient use of electric power-packs, reducing the mass penalty associated to energy storage. In this context, the CNES is actively investing its workforce and expertise in cryogenic propulsion systems in order to develop and test a flight-optimized LNG electro-pump for a 30 kN LOX-LNG engine application. In-house design tools used for the Ariane launchers development will support the conception of the machine and related multi-purpose cryogenic test bench. The project is carried on through a co-engineering partnership with ENOGIA, a well-established Organic Rankine Cycle company, that will bring to the project its expertise in turbomachines design, integration, testing and refurbishment. A passenger objective of the project is indeed the creation of a validation case for a low-cost-production business model: the CNES aims to directly evaluate the capabilities of small/medium enterprises to deliver high tech propulsion equipments. This paper describes the architecture and major design elements of the electro-pump and the related test bench, with highlights on the specific technical features and demonstration objectives associated to this concept. A global display of the performed trade-offs will show how performance and mechanical features of the equipments have been tailored in order to achieve aggressive planning and low-cost objectives, targets of primary demonstration importance. With the full-scale/cryogenic testing activities planned for end of 2019, some elements of test phase preparation will be discussed, together with short terms complementary activities and perspectives.

Keywords: Liquid-propellant rocket engines, electropump, cryogenic pumps, cryo testing, ArianeNext, turbopumps, AIT, test bench, liquid methane.

Nomenclature

ABS = Axial Balancing System
AM = Additive Manufacturing
BW = Backward Modes
CC = Combustion Chamber
COTS = Components Off The Shelf
DSP = Dynamic Seal Package

Isp = Specific Impulse
LEO = Low Earth Orbit
LN2 = Liquid Nitrogen
LNG = Liquefied Natural Gas
LOX = Liquid Oxygen
FW = Forward Modes

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1. Context

In the frame of the continuous technology evolution for space launchers applications, the CNES is actively investing its expertise in engineering and innovation with the goal of preparing the next steps for future European space vehicles. The driver of innovation in launchers is nowadays the need to simplify the access to space both in terms of launch service cost and availability. This process shall indeed pass through the simplification of all the steps taking place during the technology maturation of space systems, with the well identified targets of reducing costs and complexities of technical and management activities during the design, production-and-integration and testing phases. The launcher directorate of the CNES, whose interest in launch technology evolution has a direct and strong link with the future of the Ariane program, is promptly responding with its own strategy through its Research&Technology programs aimed to:

- improve technological solutions through innovation coming from internal R&D
- simplify production schemes and associated costs

In propulsion sector, the CNES is currently actively engaged in ambitious programs that will give a clear answer to these needs, demonstrating the reactivity of the European space community to propose ArianeNext as a full competitive launcher fleet.
Designed for low cost, simplification and reusability, the Prometheus cryogenic engine [1] will provide the Ariane future launchers with a totally new engine concept, whose differences reside strongly in the production and industrial logic, keeping all the heritage from the well validated Vulcain [2] and VINCI [3] cryogenic engines.

Facing this context, the Liquid Propulsion Research&Technology department of CNES started working on a technological and industrial challenge: the development of a high pressure electro-pump and associated test facility, fitting the requirements of a future cryogenic launcher stage and/or kick stage. The main technical challenge stands in the combination of the complexities coming high pressure cryogenics systems and those related to high power electric motors, requiring thus a strong engineering focus on materials choice, thermal and vibration handling, tribology and high power electrical generation, to name some. To face these challenges, the CNES has settled a partnership with the ENOGIA Company [4], whose strong and validated expertise in turbomachines design, innovation and production, enables the mixed-team to give quick and efficient solutions exploring all the latest evolutions in manufacturing, instrumentation and integration. In addition to the ENOGIA competences in turbomachinery development, the CNES supports the design process with its expertise in cryogenic systems and all the related engineering tools developed and validated throughout the Ariane program propulsion systems and subsystems.
The industrial challenge, important objective of this activity, is to evaluate the potential of cost-oriented conception of the turbomachine within a tight schedule from design to test validation, via a collaboration with new industrial partners standing outside of the space programs complexities and associated inertias.

2. Concept: 75 kW Class LNG Electro-Pump

The objective of the project is to develop and test an LNG electro-pump capable of providing pressurization in continuous operation and regulation of the performance over the 50%-120% speed range. Electro-pumps could indeed bring an important simplification of propulsion systems: classical solutions rely on turbine power generation, providing high performance in terms of Isp at the prize of a considerable complexity of mechanical and functional design of the entire propulsion systems. Electro-pumps could bring a significant simplification in rocket engines, getting rid of the hot gas circuits and components, and relaxing the problem of engine regulation towards control of the performance of a single element, the electric motor. These simplifications have led the choice of getting a deeper insight into this technology considering potential applications for a launcher stage. Keeping in mind constraints coming from launcher integration, the mechanical layout of the pump is designed with the minimum mass target, impacting all the components design and material choice, so to be totally representative of a flight equipment. In addition, this pump shall be designed to be LOX compatible, in the sense that a minimum set of components will be changed for a following test campaign whose aim is to validate the pump architecture under LOX operation. The working domain of the pump has been chosen on the base of CNES studies of adaptation of an electro-pumped engine cycle for a LOX-LNG engine, ending up with a target of a 30 kN engine that could be integrated in a multiple engine first stage propulsion system as well as in a high Isp upper stage.

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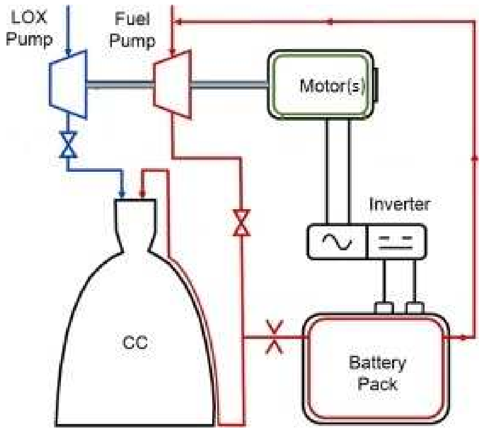

Figure 1: Example of an Electro-Pump engine cycle [5]

This configuration has been studied under the hypotheses of a mission to LEO of a launcher with an electric power-pack. Taking into account the state-of-the-art batteries weight in a configuration that shall be comparable, in terms of performance, but simpler in architecture w.r.t. classical turbine-driven solutions.
The 30 kN target identified the performance specifications of the LNG pump at the design point, essential inputs for the technology trade-offs and following preliminary design definition. The high level specifications of the LNG pump are summarized in Table 1.

Table 1: LNG pump specifications

	Design Point
Massflow [kg/s]	1.9
Inlet Pressure [bar]	4
Outlet Pressure [bar]	88
Methane Temperature [K]	110
Rotational Speed [rpm]	63’000
Electric Motor Power [kW]	75

These specifications highlight from the very beginning the complexity of the design and testing of such a machine:

- cryogenic working fluid and related thermo-mechanical design of the turbomachine and test bench
- high pressure on machine and bench components
- rotor-dynamic at high rotational speed
- electronics and control system

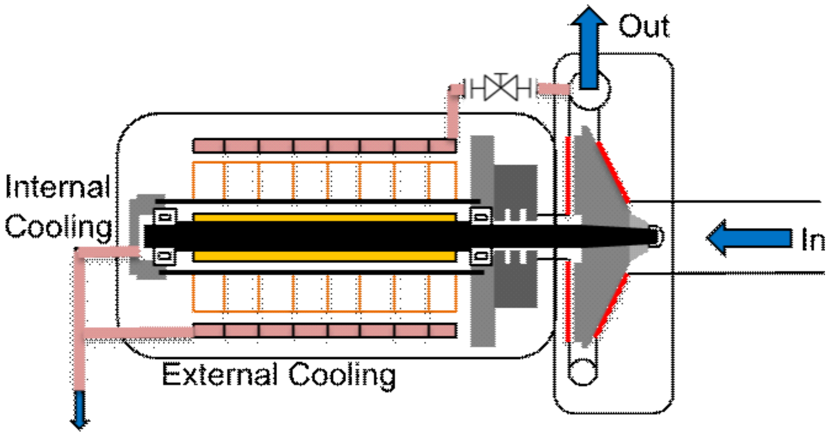

Figure 2: Scheme of the Electro-Pump

The architecture of the pump has been chosen in order to match the performance requirements with the least complexity in terms of machine integration. Different solutions have been evaluated ending up in with an architecture that includes:

- a main vane in which a suction and a centrifugal stage pump the fluid towards the outlet
- a Dynamic Seal Package (DSP) that limits the pump internal leakage, de-pressurizes the internal cooling flow
- an external cooling circuit to cool down the electric motor

Table 2: Functional architecture

Main Vane	DSP Internal Flow	Electric Motor	External Cooling
• Inducer • Impeller • Vaneless diffuser • Overhung volute	• Bladed Pump-Out-Vane • Laby-Seal	• Component-Off-The-Shelf (COTS) • Brushless Neodymium-Iron	• External jacket • Valve flow control

The electro-pump will be assembled and proof-tested at the ENOGIA facilities in Marseille (FR), then it will be integrated in its dedicated test bench and shipped to the Air Flow [6] site in Antwerp (BE) where test activities will take place. Air Flow has been chosen for its expertise in cryogenic and hazardous fluid handling, in this way the CNES/ENOGIA mixed-team can take advantage of the presence of experts in fluid interfaces management during bench calibration and operation, minimizing dead-times and consequent costs.

3. Turbomachine Design

The design process of the electro-pump has been carried on within a tight schedule (< 1 yr) thanks to a strong collaboration between the engineering and project teams of CNES and ENOGIA. All trade-offs concerning design, manufacturing and cost optimization has been supported by studies on both sides through every day exchanges and constant presence of the mixed-team in the Marseille (ENOGIA) and Paris (CNES). This process allowed to perform efficient cross-checks of proposed solutions and speeded-up the decision processes to fix the configuration and the industrial partnerships.

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3.1 Performance

The performance computations and analysis have been focused on the pump part. The motor part being designed and tested by the manufacturer.

Theses analysis were made following this logic:

A. 0D design and analysis of the pump
B. 0D design and analysis of the pump out vanes located on the back of the impeller
C. 3D CFD calculations of the rotor without volute (inducer and impeller)
D. 3D CFD calculations of the rotor with the back of the impeller and the associated leakage flow
E. 3D CFD calculations of the entire pump (rotor + pump out vane + volute)

This step by step approach was used in order to be able to justify the performance and robustness of each part. The critical performance parameters to tune through design iterations were flowrate, pressure rise and impeller axial thrust.

Figure 3 shows an example of 0D analysis of the pump out vanes resulting axial load. Several gaps between the rotor and the assembly were studied in order to find the best compromise between manufacturing tolerances and performance. The calculations have been made with a CNES tools named Ocarina.

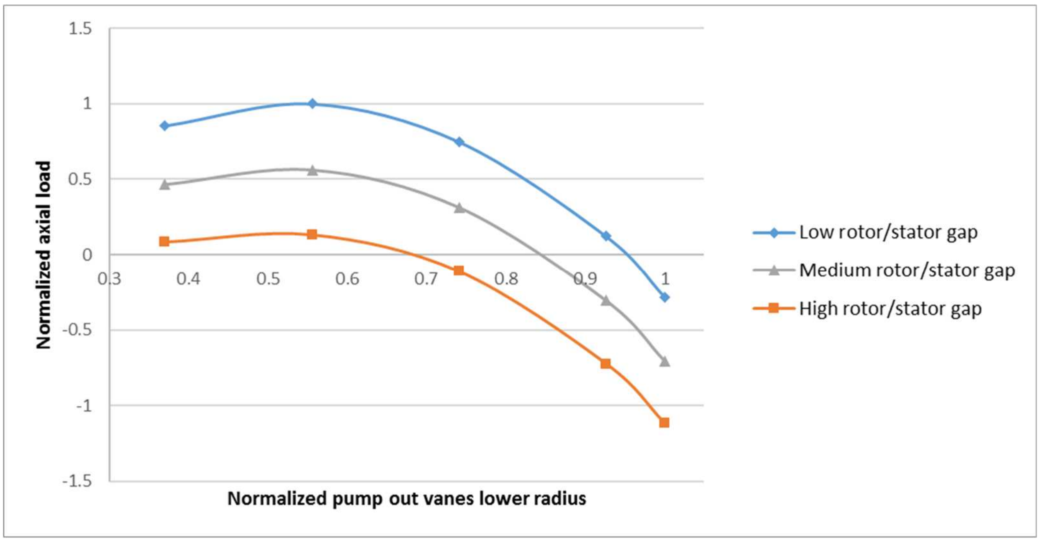

Figure 3: Axial load calculations

In line with the described design logic, 3D CFD computations followed with the goal of reinforcing the design justification. They were performed on the CNES computation cluster using the CFD code ANANAS. The flow is considered incompressible with no heat transfer.

As an example of the type of results obtained with the tool, Figure 4 shows pressure and velocity fields for case D: rotor (inducer + impeller) with the pump out vanes and leakage flow.

The calculations are 3D with the full 360° rotor considered. For simplicity sake, the results are presented using an axial slice.

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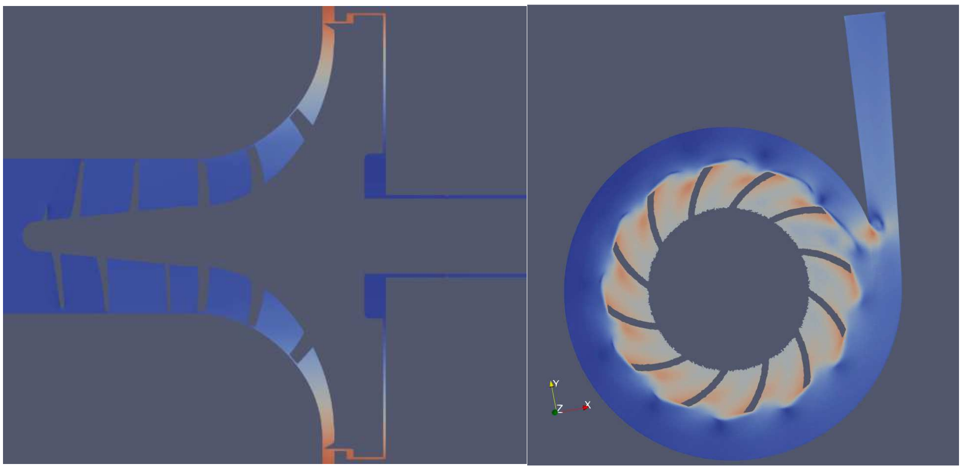

Figure 4: Pressure (left) and velocity (right) fields CFD results

On Figure 4, we can see a standard pressure rise in the main flow and the evolution of the pressure in the secondary flow going into the back of the impeller. The pressure drop inside the pump-out vanes has been compared to the 0D code in order to tune the mattering parameters and validate the design. The output boundary condition at the lower radius of the back of the impeller is an imposed pressure with two geometrical pressure drops (brutal surface changes) in order to simulate the presence of bearing and seal package. Results of velocity fields have been used in order to validate the overall performance and compute the mass flow in the secondary circuits. This allows to have a better accuracy on the mass flow requirements for the bench components (valves, cooling circuits) interacting with the pump and the motor.

3.2 Mechanics and Rotor-Dynamics

The mechanical layout is the result of the consideration of the whole set of loads acting on rotating and stator parts, accounting for static, quasi-static and dynamic load contributions.
As usual for cryogenic turbomachines the difficulty in the mechanical justification comes from the harsh environment of the working conditions, setting the focus on:

- thermo-mechanics
- high pressure loading
- vibration and rotor-dynamics
- limited choice of materials (cryogenic embrittlement)

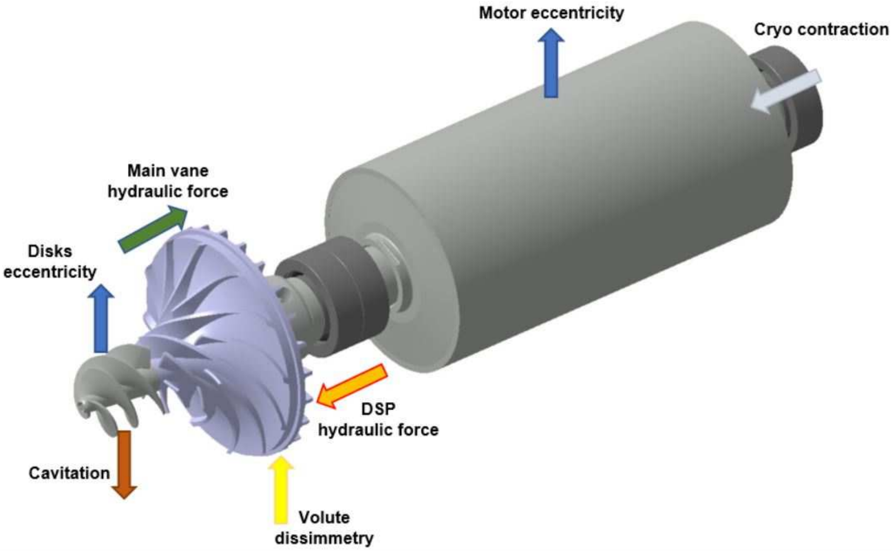

Figure 5: Rotor loads

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Several specific turbomachines design tools have been used during the design phase, some of them developed and validated by CNES through the Ariane and internal R&T programs.

The conception logic has required a set of design tools capable to chain all the design steps through an iterative process:

- RMS – Bearings operation
- OCARINA – Hydraulic axial thrust
- RotorINSA – Rotor dynamics
- ANANAS – CFD

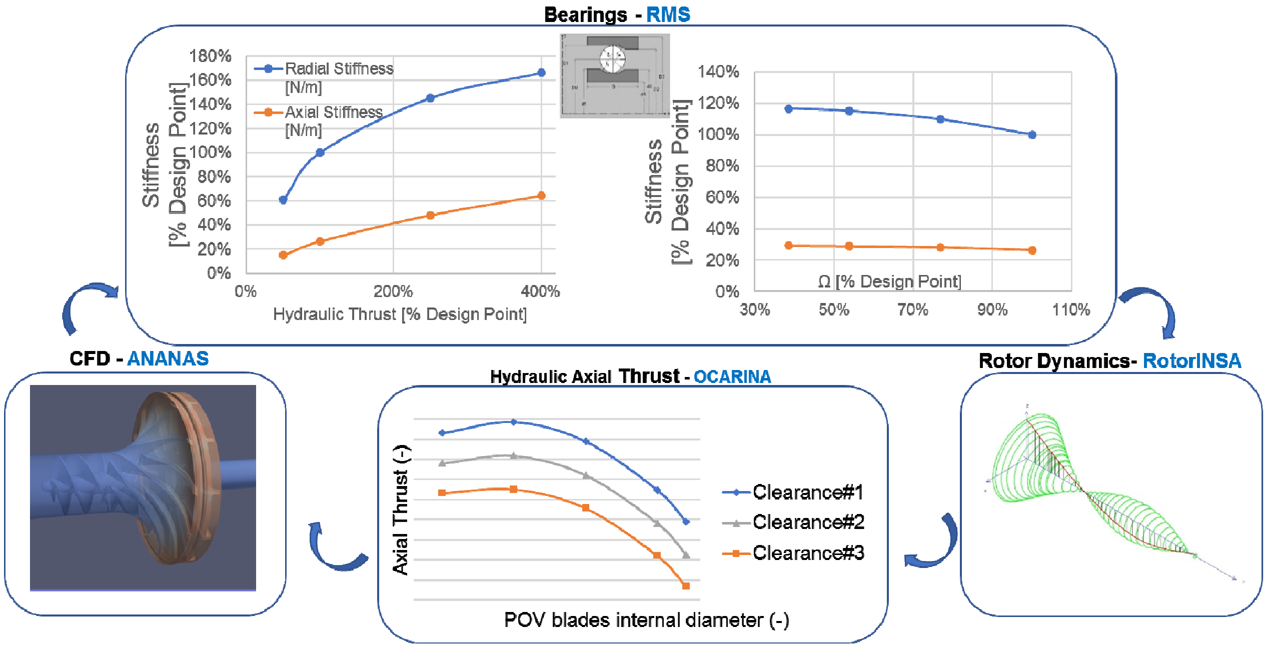

Figure 6: Design tools iterative process

Strong mechanical couplings have been observed during each design iteration, meaning that the robustness and stability criteria of the machine have only been matched through a continuous evolution of the concept through different levels of maturity.

The shaft and suspensions designs have been carried-on with the constraint of sub-critical shaft: the first critical shaft speed shall be placed above the operational range. This constraint led to the choice of the suspension system (bearing, balls material etc..) as well as the shaft dimensions and layout. This process rose the question of rotor-dynamic behavior of Electro-Pumps, which can be quite different w.r.t. classical solutions in which rigid disks are mounted on shafts. The difference stands in the internal complexity of electric motors, whose rotating parts are sub-assemblies that include rigid parts, wirings, weldings etc. (Figure 7).

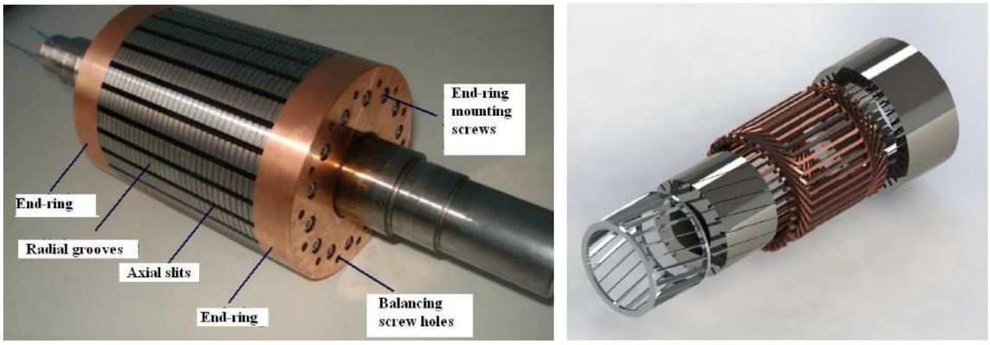

Figure 7: Internal assemblies of electric motors (rotor) [7]

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Depending on the internal motor configuration the participation to the shaft stiffness can strongly vary, and so does the first critical speed value. Different hypotheses of electric motor stiffness have been studied in order to understand the rotor-dynamic margins (Campbell diagram, Figure 8) and the forced response behavior in order to fix the admissible eccentricity level and the consequent shaft balancing procedures.

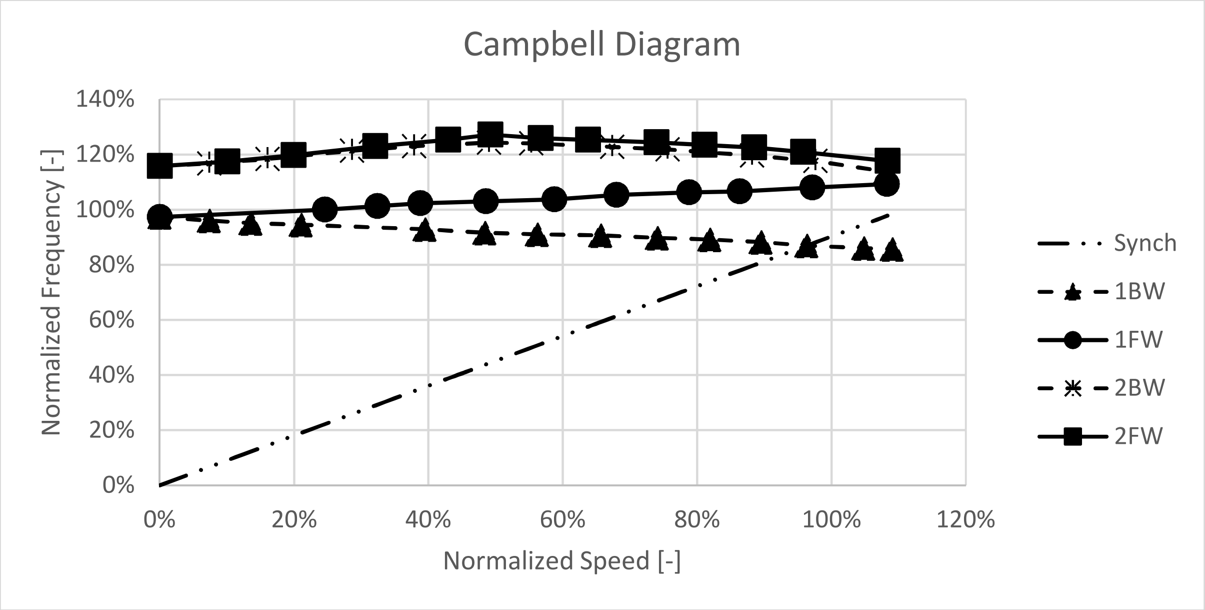

Figure 8: Electro-Pump Campbell Diagram

Those studies allowed to choose an optimal configuration for the rotor assembly, understand margins and allocate risks for the test campaign. A dedicated set of instrumentation has been integrated in the machine to monitor the vibrational behavior at shaft level (inductive displacement sensors) and at carter level (3-axes accelerometers).

Concerning the stator parts, the main challenges came from the mass optimization of the carters and cooling circuits, implying the choice of lightweight materials such as Aluminum Alloys. The mechanical justification of lightweight components has demanded several trade-offs during the assembly definition, including considerations on instrumentation compatibility and integration and, of course, strong interfaces with the fabrication processes. Innovative means of conception and fabrication have been considered in order to reduce costs and fabrication delays, this includes solutions in AM and topological optimization of highly stressed components. The concept coming from the topological optimization will be manufactured as second volute assembly, to be tested during the campaign.

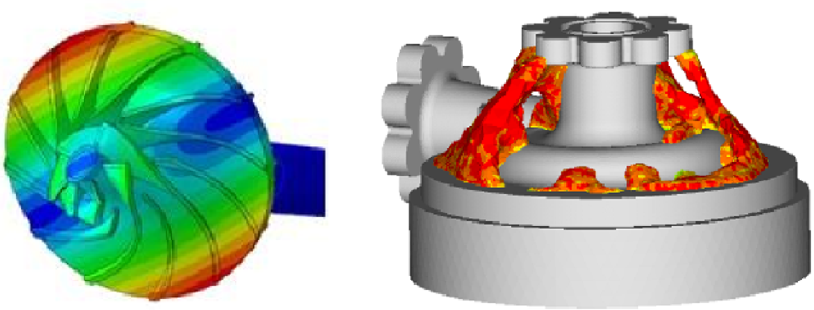

Figure 9: Modal analysis if the impeller (left) and topological optimization of the volute carter (right)

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3. Test Bench

Parallel to the development of the turbomachine, a cryogenic test bench has been designed, accounting for criteria of high flexibility of the bench and possibility to explore different working conditions of the pump. The resulting test bench is capable of feeding the pump with LNG and LN2 in a closed loop, maximizing thus the test duration. The result is an ideal set up for endurance demonstrations. The test bench is also capable of varying the pump feeding pressure, this feature will allow the exploration of the LNG pump cavitation regime.
The integration of the test platform has included a wide sourcing phase, passing from propellant handling and test facilities providers, to instrumentation and equipment. Thanks to this process, it has been possible to depict a clear display of the industrial providers of cryogenic equipments, highlighting low cost possibility through adaptation of COTS (valves, sensors, electronics) to the conditions required for cryogenic propulsion components.
As a result, a wide number of solution has been explored, ending up with a coherent design logic for a low-cost test platform.
With the goal of lowering risks and delays during the test campaign, CNES has built a complete simulation module of the test bench using the CARFONC platform [8], a fluid network simulation platform currently used at CNES for propulsion systems.

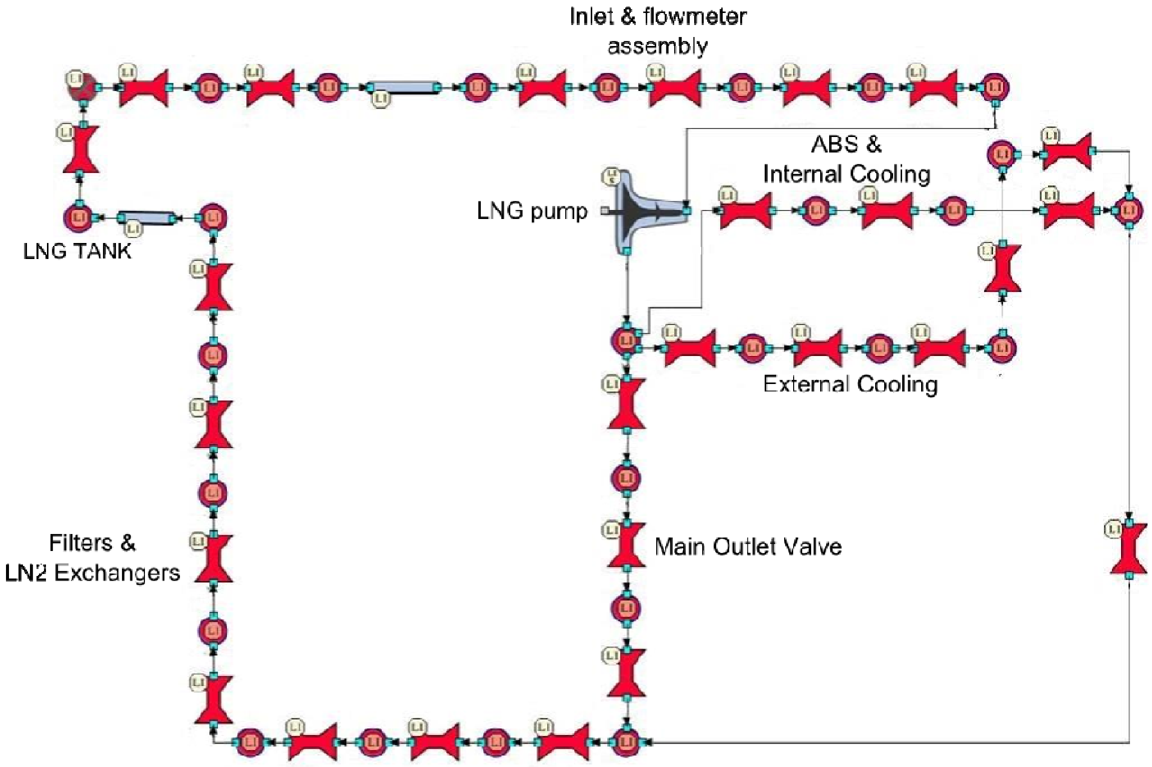

Figure 10: Test bench main circuit functional simulation module

A clear identification of the needed fluid equipment within the bench architecture has been possible thanks to the exploitation of the bench model, as well as the definition of the domain of operation, combining the pump overall performance with constraints coming from mechanical robustness of the bench components and safety considerations. This tool will benefit the test phase providing an efficient simulation module that will be at first tuned with experimental data during bench functional test, then used to give real-time prediction of bench status parameters and support eventual de-bugging operations in the case of anomalies.

4. Test Campaign and Outlook

The test campaign will be conducted in the Air Flow facilities (BE) where the assembled machine and test bench will be delivered for integration. Several demonstration objectives will be covered, from robustness proofs of the implemented technologies to performance evaluation on different working conditions. A dedicated set of instrumentation will benefit the initial experimental phases through monitoring and analysis of chill-down parameters and valves operation, in order to set an optimal scheduling and distribution of objectives throughout the campaign. Full characterization of the Electro-Pump working domain will follow, starting from nominal points performance assessment, and passing to exploration of the pump off-domain behaviour and mechanical endurance.

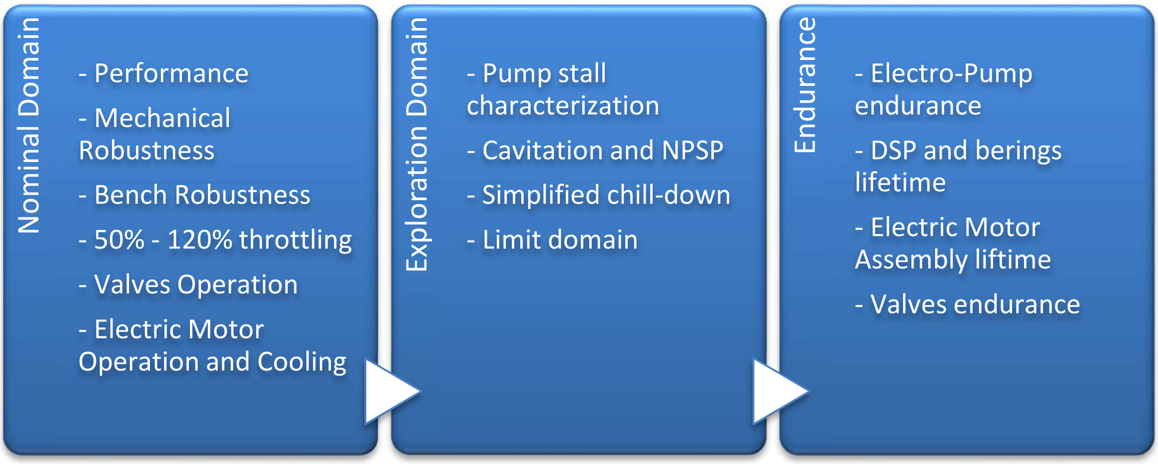

Figure 12: Test demonstration logic

The test phase will be followed by an inspection of the disassembled parts of the Electro-Pump, especially for highly loaded component such as inducer, bearings and DSP parts, crucial elements for the machine lifetime. This will give a clear understanding of the load levels reached during operation, with consequent comparison to the load set used in the design phase. Through this process the potential axes of design improvement will be identified and applied for complementary demonstration. In addition, the test platform will avail the “passenger testing” of new technologies, both during the main test phase and following prolongations, including AM printed parts with a different set of materials.

The foreseen continuation of the project includes the adaptation of the electro-pump assembly for LOX testing. Major constraints coming from LOX operation have been taken into account at every design step, only few modifications shall be included for the future LOX electro-pump. Within this logic, those demonstration activities will assess the maturity level of electric power-packs, making them a suitable technology option for launcher application.

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