Fuel Turbopump development for the LM10-MIRA LOX-LNG expander cycle engine in the frame of LYRA program

M. Rudnykh, G. Caggiano, D. Liuzzi
AVIO Spa-Space Division
Italy, 00034, Colleferro (Rome), Corso Garibaldi, 22

A.G. Kravchenko, S.V. Chembartsev
OSC «Konstruktorskoe Buro Khimavtomatiki»,
20, Voroshilov Str., Voronezh, Russia,394006

A. De Lillis, E. D'Aversa
ASI – Italian Space Agency – Launchers and Space Transportation Unit
Italy, 00133, Rome, Viale del Politecnico

Abstract
In the frame of LYRA Program founded by ASI and with ASI-Roscosmos Agreement, a 10 ton class engine (LM10 MIRA) demonstrator has been studied by AVIO-KBKhA propulsion team. New technologies linked to use of methane have been developed for injector head and fuel turbopump.
The new fuel turbopump has been designed to be implemented in the demonstrator engine. The major characteristics of the turbopump are relevant to the pump, bearings, rotor dynamics and manufacturing technology. Pump is characterized by a low volumetric flow pump with an high pressure rise made up of only one centrifugal stage. The rotor architecture choice has been done in order to have a sub-critical behaviour to reduce complexity and damping requirements. Bearings have been designed with high stiffness to guarantee the rotor dynamics leading to high speed and high diameter combination. Furthermore new technology has been dedicated to manufacture in a short time with low cost the more complex parts of the turbopump such as main housings with pump volute and turbine manifold and impeller.
Such peculiarities lead to reach a high level in the design and manufacturing aspects.

1. Introduction

Following to the activities for the development of LOX-LNG engine for new stage definition for LYRA LV, main characteristics of the flight engine has been defined and requirements given.
In order to verify the capability of an expander cycle to function in methane, and to identify the main criticalities for the flight engine development, a demonstrator program has been set up.
The demonstrator is based on existing KBKhA engine prototype but with new design of some components: a new injector plate optimized for the methane, and a new fuel turbopump.

2. Turbopump design configuration

The new fuel demonstrator turbopump has been designed for the typical objectives of a technological demonstrator i.e. technology readiness improvement, technical feasibility of the overall project in view of its development to be performed in the subsequent phase, then all the main functionalities will be tested, although it is not optimised for the use in flight.

A trade-off has been performed to identify the best TP architecture. The configuration chosen is a two stages pump (axial + radial) with one stage turbine, with balls bearings placed between pump and turbine.

Advantages of this solution are to have a sub-critical spool, a simpler architecture and a balancing procedure at low speed. Pump is characterized by a low volumetric mass flow with an high pressure rise made up of only one centrifugal stage. The diffuser and the volute are both designed in order to recover the very high dynamic pressure.
The turbine is one stage reaction and particular attention was focused on Manifold and the secondary flow optimization in order to increase the efficiency.

3. Analytical and Numerical simulations

Fluid-dynamics analysis has been performed to estimate the pump and the turbine performance characteristics and to verify the system requirements. In particular for:

- inducer and impeller to verify blades optimal design and work load, blades number and impeller splitters positioning
- diffuser correct dimensioning in term of blades number and flow deviation
- volute configuration to increase its diffusive capabilities
- turbine inlet manifold optimization to guarantee a uniform circumferential distribution of the mass flow to the turbine stator
- turbine stator and rotor to define the best blade profiles, work load splitting and secondary flow minimization

Mechanical assessment has been performed to verify Low and High Cycle Fatigue requirements (LCF, HCF) and strength margins.
Secondary systems has been designed in order to ensure:

- an Axial Balancing System (ABS) dedicated to balance the axial resultant thrust acting on rotor in order to reduce the axial loads that the bearings should support. The axial thrust is generated by the pressure action on the pump and turbine rotors surfaces and by momentum variation in the fluid dynamic channels:
- a bearing cooling circuit dedicated to guarantee the flow in order to keep bearing temperature down to prevent overheating and consequent failure;
- a sealing system dedicated to optimise the leakages and re-circulating flow rates to guarantee systems correct behaviour and safety requirements.

A further step, made up of deeper simulation analyses, has been performed in order to reduce the predicted accuracy on pump and turbine performance and to ensure engine functioning behaviour.

4. Technological aspects

A new technology has been dedicated to manufacture in a short time with lower costs the more complex parts of the turbopump such as main housings (with pump volute), turbine manifold and impeller. These parts have been produced by additive technology: Direct Metal Laser Sintering.

Figure 1: - LM10 MIRA CH4 pump impeller produced by DMLS technique.

Such innovation has provided a significant advantage with respect to the previous experience. Parts manufacturing do not need, for example, time and cost linked to casting tools. Moreover modifications of the parts, in the frame of the turbopump development, are possible without having an impact on not-recurring costs. Only 3D model updating is required.

Figure 2: - LM10 MIRA CH4 turbine manifold produced by DMLS technic.

Figure 3: - LM10 MIRA CH4 pump volute produced by DMLS technic.

5. Experimental investigations

In order to ensure the design solutions and to reduce the predicted accuracy on pump and turbine performance and bearing reliability the testing activities of turbopump sub systems has been performed. In particular:

- Turbine inlet Stator test campaign;
- pump testing in water;
- bearing testing.

5.1 Turbine inlet Stator test campaign

The Test Article is constituted by the turbine inlet manifold and stator row, without rotating parts. The scale factor is equal to unity. One manifold has been used for the tests, while three turbine stators characterized by three different serial numbers have been tested.
The key objectives for test campaign were:

- to verify the correct behaviour of manifold and vane in terms of Flow Function VS Pressure Ratio diagram;
- to verify that flow coming from the manifold inlet is correctly distributed among all the vanes;
- to verify that Manifold and Vane losses are in line with predictions.

Specific huge instrumentation has been implemented in order to evaluate relevant objectives

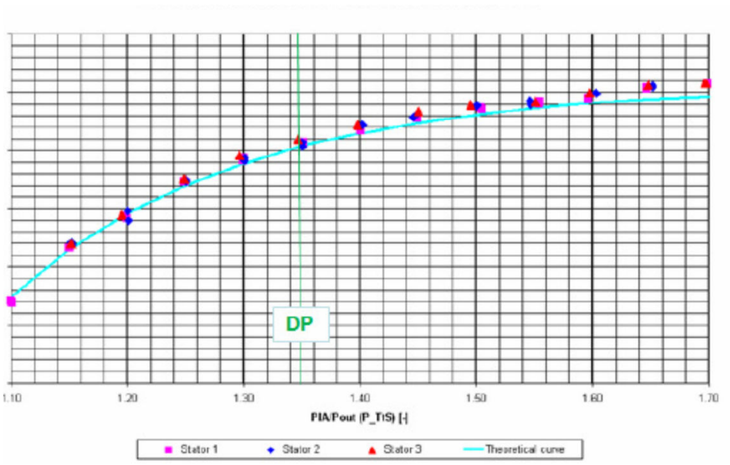

Figure 4: - LM10 MIRA CH4 Manifold + stator mass flow rate characterisation.

Obtained results have put in evidence the correct behaviour of the rig and the achievement of test campaign objectives. Results are in line with model predictions and promising to achieve turbine performance on engine tests.

5.2 Pump testing in water

To perform pump water test campaign a specific Test rig has been designed and manufactured. The test article is reproduced by following:

- Inducer and impeller: the same part number of turbopump in order to be able, if required, to choose by test which is the serial number to be implemented in the turbopump.
- Volute: the same part number of turbopump modified for specific instrumentation needs
- Diffuser and backplate: different part numbers in order to implement specific instrumentation.

The objectives of the test campaign are:

- validation of the pump hydraulic design;
- pump performance assessment in absence of cavitation for one rotational speed, within the specified pump flow coefficient range;
- pump performance assessment in cavitating regimes for one rotational speed, within the specified pump flow coefficient range;
- identification of NPSPinc (first appearance of cavitation) within the specified pump flow coefficient range;
- identification of critical NPSP corresponding to the 4% pump pressure rise decay within the specified pump flow coefficient range;

- measurement of pump axial loads in non-cavitating and cavitating regimes;
- verification of axial balancing system correct functioning;
- turbopump bearing circuit simulation (no turbopump bearing is installed as test article)

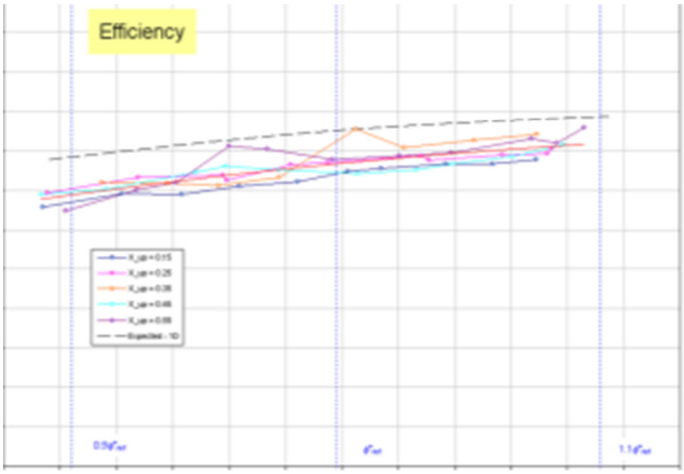

Figure 5: - LM10 MIRA CH4 pump efficiency.

There are following conclusions coming from pump water test campaign:
- Good pump behaviour;
- Inducer pressure rise is little bit lower respect CFD analysis;
- Cavitation tests in water showed good agreement with prediction.
- Back plate pressure drop is a little bit higher than the CFD analysis;
- Shroud pressure drop is lower than the CFD analysis;

Obtained results have put in evidence the correct behavior of the test article and the achievement of test campaign objectives. Results are in line with model predictions and promising to achieve pump performance on engine tests.

5.3 Bearing testing

Bearings are going to be tested in liquid nitrogen in order to evaluate the design before the methane bench availability. This decision has been supported by several considerations. Liquid nitrogen can be considered as an alternative to liquid methane, in terms of flow field (Reynolds numbers and equal volumetric flow rate) and thermal cooling behaviour (Nusselt number) taking into account the temperature difference between fluids (about 115 K in methane and 80 K in nitrogen).
In liquid nitrogen environment, taking into account the bench limitations, the bearings operating conditions are severer (especially for the turbine side ones), because they are closer to liquid/gas transition. Methane status in the turbopump is in supercritic phase (therefore no liquid/gas transition). Tribological impact difference between methane and nitrogen has been considered as minor.
Turbopump bearings testing in liquid nitrogen can then provide important experimental evidences for bearings design validation prior it's testing in liquid methane.
To perform bearing test campaign a specific Test rig has been designed and manufactured. The circuit of the flow through the bearing has been reproduced according to the turbopump configuration.

The main objectives of the test campaign are as follows:
- to verify and confirm bearing capabilities to withstand mechanical load at the maximum speed of turbopump envelope in cryogenic environment
- to verify fluid pressure and temperature evolutions through bearings
- to verify the life time.

For the time been the first part of the test campaign has been completed. The maximum rotation speed has been achieved. This first part has provided an important information relevant to bearing power dissipation and temperature increase. After test bearings have been dismounted for deep material inspection.
The logic of the test foresees to perform the second part of the test campaign where the lifetime and margin to extreme loads will be investigated.

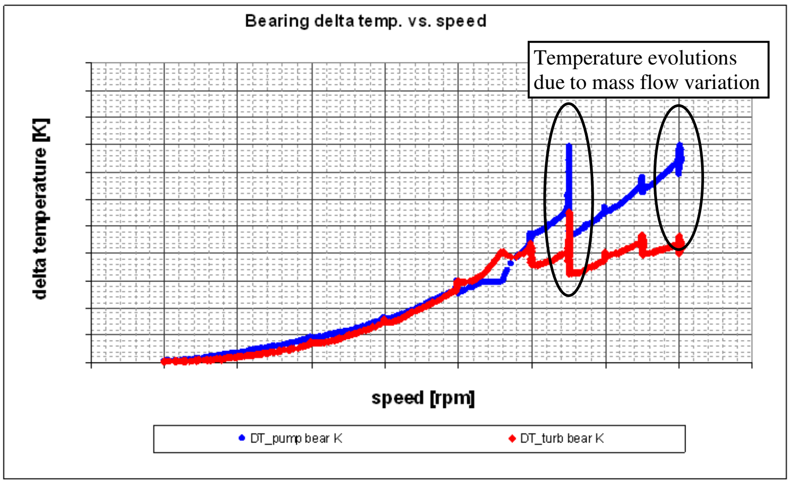

Figure 6: - LM10 MIRA bearing test results.

Figure 7: - LM10 MIRA bearing test rig in chill down conditions.

6. Conclusions

LM10 MIRA demonstrator fuel turbopump design in the frame of LYRA Program has achieved the final phase of the development, when the subsystem tests are quite completed. Experimental results (reached up to now) confirm analytical simulations and ensure that technical solution implemented in the design have been selected correctly. New additive technology used ~~for~~ to manufacture in a shorter time with lower cost the more complex parts of the turbopump are considered as very useful.

The final verification of completely assembled turbopump is foreseen in the frame of demonstrator engine firing test campaign within year 2013.

References

[1] L. Arione, D. Scarpino, M. Ciranna, M. Rudnykh, G. Caggiano, A. De Lillis, E.D'Aversa, S.D. Lobov, V.P. Kosmacheva, S.V. Chembartsev, A.A. Gurtovoi. Development of new technologies applied to LOX-LCH_4 Propulsion. 63rd International Astronautical Congress, Naples, Italy, 2012.

[2] L. Arione, N. Ierardo, M. Rudnykh, G. Caggiano, A. De Lillis, E.D'Aversa, S. Lobov, A. Shostak, Development status of the LM10-MIRA LOX-LNG Expander Cycle Engine for the LYRA Launch Vehicle. Space Propulsion, San Sebastian, Spain, 2010.