LUMEN Turbopump - Design and Manufacturing of the LUMEN LOX and LNG Turbopump components

By Tobias Traudt[a], Robson dos Santos Hahn[a], Thomas Mason[a], Christian Mader[a], Jan Deeken[a], Michael Oschwald[a], Stefan Schlechtriem[a]

[1)] *Institute of Space Propulsion, German Aerospace Center, DLR, Hardthausen, Germany*

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In the LUMEN project (**l**iquid **u**pper stage de**m**onstrator **en**gine) an expander bleed engine will be built at the DLR to allow component research on engine level. The LUMEN engine will feature two dedicated turbopumps, one for LOX and one for LNG. The turbopumps design is modular to develop sophisticated turbopump components in a representative engine cycle.

In this work we will give an overview over the status of the development. The turbopumps critical design has been finished and is ready for manufacture. To finalize the pump design, CFD simulations of the LNG pump impeller have been improved from previous work by incorporating losses due to the pump sealings and the flow between rotor and housing.[1)] The rotor dynamics analysis for the LOX and the LNG turbopump will be discussed. The design considerations will be presented which ensure operation below the first critical speed for both turbopumps.

Finally, we will give an update on the status of the Cryogenic Sealing and Bearing Test Bench (CSBT) and the modular turbopump test bench (MTB), which are in construction for the validation of the turbopump design.

Key Words: LUMEN, engine demonstrator, LOX/LNG, turbopump, rotordynamics

1. Introduction and background

LUMEN (**l**iquid **u**pper stage de**m**onstrator **en**gine) is a project at the DLR in which a liquid rocket engine will be designed, built and tested at the DLR test bench P8.3. LUMEN is an expander cycle engine with a nominal thrust of 25kN. It will not be flight hardware, but instead is intended for test bench use. It will be designed in a modular way with easy access to all components to allow for component research on system level. The focus of the engine to test bench and research use leads to some unusual design choices which are summarized in Ref. 2) for the engine cycle. For example there will be two turbopumps instead of one single shaft turbopump which is a common approach to a turbopump for a LOX/LNG rocket engine. There are also unusual choices related to the turbopump design of the LUMEN demonstrator engine which are summarized in Ref. 1). There are two points which are important in this work: The decision not to use an inducer for the first phase of operation and the lubrication of the bearings by oil. Since LUMEN is a demonstrator engine the inducer pressure rise can be replaced by an increase of interface pressure at the test bench. This has the advantage that there is no need to design and characterize an inducer and in the case of the Oxygen turbopump (OTP) there is no risk of oxygen fire if the inducer comes in contact with the housing. Without inducer the impeller has to be designed for zero swirl at the inlet.

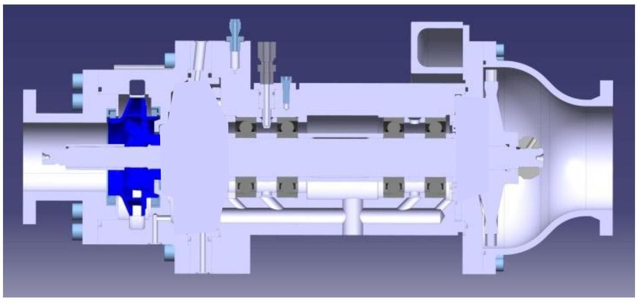

Figure 1: CAD model of the LOX turbopump

There are two reasons for the oil lubrication: life expectancy and modularity. The first point is of importance for the intended component research at the DLR test bench P8.3. It is a project requirement, that the turbopumps can be used for one test campaign without maintenance. The second point is of importance for turbopumps intended for research. By using oil lubricated bearings, the pumped fluid is not used for the cooling of the bearings and the main components (pump, bearing/shaft assembly and turbine) become three independent systems. This way it is possible to change either the pump or the turbine or both without having to do a significant redesign of the turbopump.

In this work we will give an overview on the current design status and on the manufacturing of the LUMEN turbopump parts.

2. Operational parameters of the turbopumps

Recent changes in the design of the LUMEN engine cycle which are mainly driven by advances in the design of the combustor cooling channels make it necessary to change the operational envelope of the turbopumps.[2)] For example the discharge pressure of the LNG pump had to be raised in order to enhance the performance of the cooling channels (see Table 1). There is no need to redesign the LNG pump impeller because the new upper load point is within 120% of the design point.

Table 1: new operational parameters at the nominal point

	OTP	FTP
pump pressure rise, [bar]	72	115
pump power, kW	80	214
rotational speed, [rpm]	24000	50000

The rotational speed had to be raised in order to reach the new discharge pressure / volume flow pair. This is possible with the current design, but it will decrease the distance between to the first critical speed as we will show in section 4.

3. Design of LNG pump and pump seals

In Ref. 1) the performance of the LNG pump impeller has been verified by simulations with Ansys CFX. The analysis showed that the performance is higher than expected supposedly because the sealing losses and the housing/impeller flow were neglected. The CFD analysis has since been updated to incorporate these losses. Several impeller seal designs have been simulated to investigate the leakage. Floating ring seals are the baseline design and have a leakage of 8.2% of the bulk flow of the impeller. Additionally, a labyrinth seal was added to the front and back of the impeller. Figure 2 shows the computational domain in the case of a labyrinth seal. This seal type has a leakage of 6.4% of impeller bulk flow.

Simulating the flow between housing and impeller makes it possible to get a measure for the losses that appear in this area. Another benefit is that a realistic flow in this area will result in realistic inlet conditions to the impeller seal which is important for leakage and for the calculation of the rotor dynamic coefficients. In the streamlines in Figure 2 it is easy to see the angle of attack of the flow towards the stepped seal.

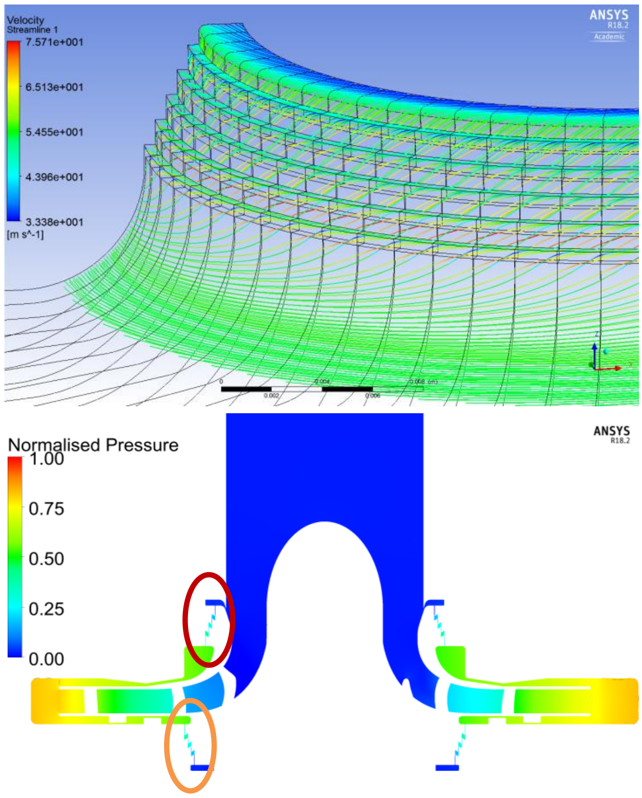

Figure 2: computational domain of improved LNG impeller simulation with stepped front seal (red) and back seal (orange)

4. Rotor dynamic analysis

The rotor dynamic analysis has been done for the rotor assembly with a DLR in-house tool called ROTAN. The tool is based on RotFE.[3)] ROTAN is a tool for systematic rotor dynamic analysis and it is able to automatically simulate combinations of input parameters. A detailed description on the capabilities of ROTAN can be found in Ref. 1). A parameter variation has been performed to estimate the critical speed of the OTP and FTP and to evaluate the sensitivity of the solution to the respective parameter. The following is varied

- *impeller weight*
- *turbine weight*
- *bearing and shaft diameter*
- *with and without pumps seals*
- *shaft sections lengths*

It is obvious that an increase in shaft diameter leads to an increase in the first critical speed. The shaft diameter also increases the bearing diameter and both parameters together are responsible for the biggest change. An increase in diameter from 30 to 50mm increases the critical speed by 40%. Despite of the big influence on the critical speed the diameter is not increased in the final design, because of a trade-off. The bearings with 40mm or 50mm inner diameter have a speed rating which is not high enough for our application.

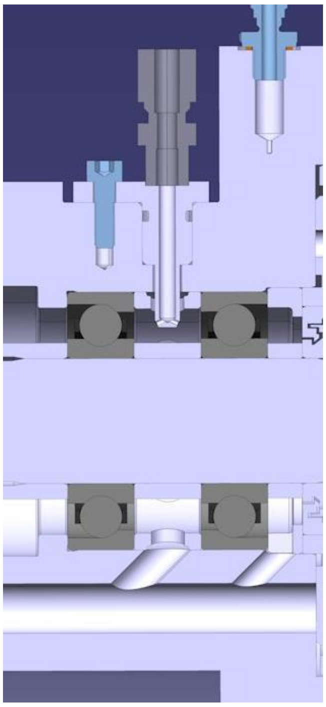

Figure 3: oil injection port configuration

The turbine weight is the second biggest influence. Reducing the weight from 1.4kg to 0.8kg increases the critical speed by 28%. This change however is only possible if a lightweight titanium alloy can be used which is not possible in our case, because of the turbine entry temperature.

The impeller weight is only of importance for the FTP. The OTP rotor dynamics is dominated by the turbine.

The pump impeller seals have a large impact and our analysis showed that it is mandatory to do a rotor dynamic analysis with impeller seals. The model which is implemented in ROTAN is suitable for straight gap floating ring seals. It is not suitable for stepped seals like the one simulated in section 3. For this reason the first turbopump design will have floating ring seals, but work has been started to do a coupled fluid structure simulation with stepped seals in order to calculate the rotor dynamic coefficients. The coefficients will then be used in Rotan to see if future designs are able to use the improved stepped seals.

With all the considerations above the critical speeds of both turbopumps are calculated and shown in Table 2.

Table 2: critical speeds of the turbopumps

	Critical Speed [rpm]
OTP	50000
FTP	63000

The maximum rotational speed of the OTP is 28000rpm. 50000rpm critical speed translates to a margin of 78%. For the FTP the maximum rotational speed is 57000rpm and hence the margin is 10%. Tests will be used to verify if this margin is sufficient.

5. Bearing and Lubrication System

The LUMEN turbopumps bearing system is the same for the OTP and the FTP. There are two pairs of hybrid bearings with steel races and ceramic balls. The bearings are arranged in an O-configuration which is beneficial for rotor dynamics due to an increased stiffness.

In the case of the LNG turbopump the DN number for the bearings is $n \cdot d_m = 57000 min^{-1} \cdot 46mm = 2.6 \cdot 10^6$. Oil Jet lubrications has been chosen because the bearing manufacturer claims it is already in use up to a DN number of $4 \cdot 10^6\ \mathrm{min}^{-1}\, mm$.[4)] It is necessary to inject the oil into each bearing individually because the oil jet velocity is not high enough to reach a second bearing row at the rotational speeds which are foreseen for the FTP. For this reason the injection location is in between each bearing pair (see Figure 3). The injection pressure will be 4bar and the injection velocity will be app. 20m/s.

The hole for the oil jet assembly will be used for optical post-test inspection of the bearings.

6. Test benches

For component testing DLR will build two test benches. The test benches will complement national and european testing capabilities for turbopump components and improve the testing opportunities DLR can offer to interested partners.

6.1 Cryogenic sealing and bearing test bench (CSBT)

The CSBT will be used to test bearings and sealings in a representative environment. It will make use of the cryogenic equipment installed at the DLR test bench M3.5.[5] There will be a supply of liquid nitrogen (LN2) and liquid oxygen (LOX) with pressures of up to 50bar and a mass flow of up to 2kgs/s. An electrical motor will be used to drive the test specimens up to a rotational speed of 60.000rpm.

The preliminary design foresees radial loads of up to 50kN and axial loads of up to 30kN for bearings tests. The loads will be applied by springs.

The electrical motor will also be used for testing sealing systems. Especially the seal performance in terms of leakage and power losses is of interest, but the CSBT is also envisioned for characterizing the rotor dynamic coefficients of seals.

6.2 Modular Turbopump Test Bench (MTB)

The MTB will be used for turbine, for pump and for turbopump testing. The MTBs size has been chosen so that it is suitable for tests of most turbopumps and their components in the 75kN engine class. A concept study has been performed for the MTB and a concept has been chosen from the ones presented in 2017.[6] The MTB will use a generator which is either driven by the tested turbine or which can be used as an electrical motor to drive pumps. Because of the design trade-offs which were made during the concept study, the test bench was renamed from *modular turbine test specimen* to *modular turbopump test bench.*

Table 3: specifications MTP

Parameter	Unit	Value
max. pressure turbine inlet	bar	100
max. rotational speed	rpm	60000
max. mass flow GN2	kg/s	4
max. mass flow GH2	kg/s	1.5
max. turbine power	kW	500
optional turbine power	MW	1
turbine media	-	GN2, GH2
pump media	-	H_2O, LOX, LNG LH2

The main specifications are shown in Table 3. The generator power will be 500kW with an option on 1MW if two generators are used.

The media necessary to drive a turbine or to feed a pump will come from DLR test benches at which the MTB will be used (P6.2 and P8). This way it is possible to do tests either with gaseous nitrogen (GN2) or gaseous hydrogen for turbines and water or LOX or LNG or LH2 for pumps. Because the MTB will have all valves and supply systems for pumps and turbines and safety installations for these tests like a containment, it can also be used to test turbopump assemblies with the fluids mentioned before.

7. Conclusion

The current development status of LUMEN turbopump components has been presented. Engine cycle changes and their impact on the design have been discussed.

The pump simulation has been enhanced by incorporating the pump seals and the housing/impeller flow into the simulation. With the improved simulation it is now possible to calculate the complete losses of the impeller.

In a rotor dynamic analysis the layout of the turbopump has been finalized. Subcritical operation of OTP and FTP is confirmed.

The bearing and lubrication system has been presented. Oil jet lubrication is used because it is proven at high operational speeds and it will maximize maintenance intervals.

References

1) T. Traudt, R. Santos Hahn, H. Negishi, F. Lindemann, S. Woidich, B. Wagner, D. Maier, C. Mader, G. Waxenegger-Wilfing, J. Deeken, M. Oschwald und S. Schlechtriem, „Status of the Turbopump Development in the LUMEN Project,“ in *69th International Astronautical Congress*, Bremen, 2018.

2) J. Deeken, M. Oschwald und S. Schlechtriem, „LUMEN Demonstrator- Project Overview,“ in *32nd International Symposium on Space Technology and Science, Fukui, Japan*, 2019.

3) I. Bucher, *RotFE*, 2010, https://www.mathworks.com/matlabcentral/fileexchange/28563-rotor-dynamics-toolbox-rotfe (accessed octobre 5, 2018)

4) FAG, „Schmierung von Wälzlagern,“ 2002, https://www.schaeffler.com/remotemedien/media/_shared_media/08_media_library/01_publications/schaeffler_2/publication/downloads_18/wl_81115_4_de_de.pdf (accessed

january 8, 2019)

5) T. Traudt, C. Bombardieri und C. Manfletti, „High Speed Imaging of Water Hammer with Column Separation,“ in *Pressure Surges Conference, Dublin*, 2015.

6) T. Traudt, G. Waxenegger-Wilfing, R. Santos Hahn, B. Wagner und J. Deeken, „An overview on the turbopump Roadmap for the Lumen Demonstrator engine and on the new turbine test facility,“ in *IAC, Adelaide, Australia*, 2017.