A Test Facility for the Lifetime Characterization of Cryogenic High-Speed Bearings

Angelo Pasini[1], Riccardo Simi[2], Gabriele Brotini[3], Alessandro Apollonio[4], and Luca d'Agostino[5]
University of Pisa - Department of Civil and Industrial Engineering, Pisa, Italy, 56122

Marco De Rosa[6] and Marco Leonardi[7]
ESTEC - European Space Research and Technology Centre, Keplerlaan 1 - P.O. Box 299 NL-2200 AG Noordwijk ZH, The Netherlands

Currently, reusable rockets are the most promising design solution to reduce launcher costs. A truly reusable rocket engine to be economically viable should ensure the increase of frequency launch with virtually no maintenance effort. The rocket engine reusability can be reached by developing long-life turbopumps with a lifetime requirement of several hours. The replacement of rolling bearing, which represents a critical component for reusability, with journal bearing has been considered the most promising solution to increase turbopump lifetime. The propulsion team of the Department of Civil and Industrial Engineering of the University of Pisa, UniPi, is currently pursuing the development of high-speed hybrid bearings for reusable pump-fed liquid rocket engines in the framework of the ESA's project "Long Life Journal Bearings for Turbopumps." UniPi's team selected the two most promising candidate journal bearings: a square-recessed journal bearing with 45° orifices, a radial-orifice compensated bearing. Inconel 718 and ceramic matrix composite, CMC, are the chosen materials that minimize the possible surface wear of the bearings and ensure the material compatibility with LCH4. The geometry and material configurations will be tested in a cryogenic test facility suitably developed to characterize the performance of journal bearings employing liquid methane in a representative turbopump environment of future pump-fed LOX-CH4 rocket engines. This paper illustrates the selection of the test journal bearings and presents the novel test apparatus, and a facility designed for the bearing experimental lifetime characterization.

I. Nomenclature

CMC = Ceramic Matrix Composite
FMS = Fluid Management System

[1] Assistant Professor, Department of Civil and Industrial Engineering, angelo.pasini@unipi.it
[2] Researcher, Department of Civil and Industrial Engineering, riccardo.simi@ing.unipi.it
[3] Researcher, Department of Civil and Industrial Engineering, g.brotini@studenti.unipi.it
[4] Researcher, Department of Civil and Industrial Engineering, alessandro.apollonio@ing.unipi.it
[5] Full Professor, Department of Civil and Industrial Engineering, luca.dagostino@ing.unipi.it
[6] Chemical Propulsion Engineer, ESTEC - European Space Research and Technology Centre, marco.de.rosa@esa.int
[7] Chemical Propulsion Engineer, ESTEC - European Space Research and Technology Centre, marco.leonardi@esa.int

F_D = Dynamic load
F_S = Static load
p_s = supply pressure
p_{start} = starting supply pressure
UniPi = University of Pisa

II. Introduction

Currently, reusable rockets are the most promising design solution to reduce launcher costs. A reusable rocket engine to be economically viable should ensure the increase of launch frequency with virtually no maintenance effort. Rocket engines that employ liquid propellants, due to their superior throttleability and simplicity of refueling compared to solid propellants, are the most promising engine technology to fully meet the reusability requirement for the next generation of first-stage engines.

The Space Shuttle was the first reusable spacecraft, and the maintenance of turbomachinery of the SSMEs (Space Shuttle Main Engines) represented a significant recurring cost [1]. One of the most critical SSMEs components were the turbopump's bearings. These hybrid bearings, with ceramic balls and metallic races, could sustain at most 5-6 launches [1]. In 1969, Reddecliff and Vohr at Pratt & Whitney Aircraft and Mechanical Technologies Incorporated designed and tested for the first time two hydrostatic journal bearings employing cryogenic fluids, LH2 and LOX [2]. The bearing working in LOX was designed in a tandem configuration with a ball bearing. The latter is installed in a rotating cartridge, which is the journal component of a hydrostatic bearing. Reddecliff and Vohr's research suggested that hydrostatic bearings could replace rolling bearings increasing bearing lifetime.

In 1992, Rocketdyne performed a series of tests on a retrofitted version of the Space Shuttle Main Engine (SSME) high-pressure oxygen turbopump (HPOTP) with hydrostatic bearings [3,4]. Pratt & Whitney completed in 1998 the design and manufacturing of the Advanced Liquid Hydrogen (ALH) turbopump in the context of the research program designated "Integral High Payoff Rocket Propulsion Technology" (IHPRPT) [5,6]. A turbopump equipped with two hydrostatic bearings was tested, and it was observed large supersynchronous vibrations at low speed. The inspection of the bearings surface showed signs of rubbings at several locations [7]. These studies suggested that one of the most critical disadvantages of a journal bearing is its inevitable wear during transient regimes [7].

At the Mechanical Engineering Department of Texas A&M University, different journal bearing geometries were tested [8–11]. The various experimental campaigns define how the journal bearing performance was influenced by supply pressure, shaft speed, pressure drop, recess geometries, and orifice dimensions. Tests were carried out by means of a facility that implement water instead of hazardous cryogenic fluids.

Advanced research on journal bearings were performed also in Japan. Oike et al. tested journal bearing at JAXA Kakuda Research Center. They designed and tested journal bearing with young-leaf and square recess shapes using liquid nitrogen as lubricating fluid [12].

Journal bearings are a promising technology to improve engine lifetime [3,13,14]. Therefore, in Europe, the French national space agency, CNES, with the Safran group, performed a demonstration program of LH2 turbopump equipped with journal bearing [15,16]. Also, at the Liege University, a journal bearing built-in Ceramic matrix composites (CMC) technology for liquid oxygen applications was tested [17].

To pursue the competitiveness of the European space sector, the European Space Agency supports the development of critical technologies for rocket engine reusability. The propulsion team of the University of Pisa, UniPi, is currently pursuing the development of high-speed journal bearings for reusable pump-fed liquid rocket engines in the framework of the ESA's project "Long Life Journal Bearings for Turbopumps."

The present paper introduces the novel test apparatus and a facility designed for the experimental lifetime characterization of the journal bearings.

III. Long-Life Turbopump Requirements

Nowadays, LOX/LCH4 is one of the most promising cryogenic bipropellant combinations [18]. Compared to liquid hydrogen fuel, liquid methane has longer and easier storage and higher density [19]. Moreover, due to the low difference in liquid density from oxygen to methane, LOX/LCH4 turbopump could be designed with a single shaft. Furthermore, LOX/LCH4 is a candidate for the next generation of reusable launch vehicles.

A turbopump for a reusable rocket engine has to ensure a cumulated lifetime requirement of 4800 s involving 60 operating cycles [20]. The research activities performed by Airbus Safran Launchers in cooperation with IHI

Corporation [21] reported the development of LOX/LCH4 turbopump for a small reusable booster or micro-launcher first stage engine. Also, the ArianGroup is currently developing a LOX/LCH4 first stage engine for the next generation of launchers after Ariane 6 [18]. Due to the absence of performance data concerning LOX/LCH4 turbopump and bearing requirements, the UniPi's propulsion team took advantage from the above research activities in order to carry out a preliminary design of an LOX/LCH4 engine. Table 1 reports the main characteristics of a reference LOX/LCH4 engine. These characteristics were employed to perform a preliminary design of a turbopump, called UniPi LCH4 TP (Table 2). Fig. 1 shows a preliminary scheme of the UniPi LCH4 TP that could be equipped with two journal bearings.

Table 1 Reference LOX/LCH4 engine.

Main engine characteristic	Value
Propellants	LOX, LCH4
Engine cycle	Gas generator
Thrust in vacuum	900 kN
Thrust at sea level	750 kN
Throttleability	75 ÷ 100%
Mixture ratio O/F	3.4
Theoretical vacuum specific impulse	327 s (estimated)
Lifetime	> 60 cycles > 4800 s (cumulated)

Table 2 LCH4-turbopump main characteristics.

UniPi LCH4 TP Characteristics	Value
Propellant	LCH4
Turbopump architecture	1 one-stage centrifugal pump and 1 turbine on a single shaft
Rotational speed	20000 rpm
Pump specific speed	0.4 (1028 in US nomenclature)
Shaft power at the pump	2.4 MW

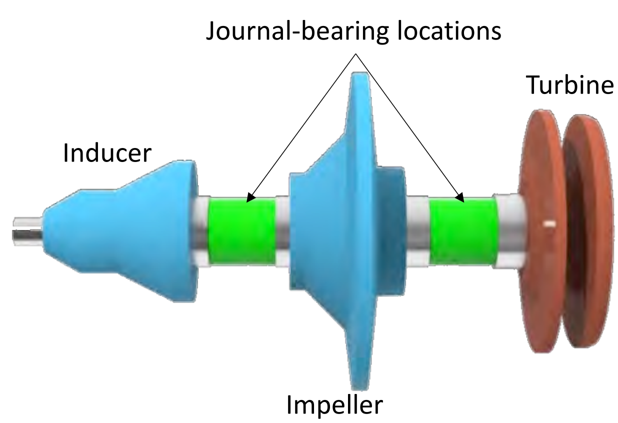


Fig. 1 Schematic view of the preliminary designed turbopump.

Table 3 reports the requirements that journal bearings should fully meet to ensure the UniPi-LCH4-TP performances. The lifetime and lubricant type affect mainly the journal-bearing material.

Table 3 Technical specifications of the journal bearings.

Requirement	Value
Journal bearing lubricant	LCH4
Supply pressure	3.5 ÷ 50 bar
Maximum supply volumetric flow rate	2 L/s
Maximum bearing diameter	85 mm
Maximum length-to-diameter ratio	1
Maximum clearance	50 μm
Stationary rotational speed	20000 rpm
Minimum direct stiffness	36 MN/m
Maximum start-up time	3 s
Maximum shut off time	4 s
Lifetime	> 260 cycles > 10 hours (cumulated)

The UniPi's propulsion team developed several analytical and numerical models, including the fluid turbulence and inertia effects, for the estimations of journal bearings performance. Both types of models have been implemented to design orifice compensated or recessed journal bearings. The models are capable of predicting the bearing flow rate and stiffness at steady-state operating conditions, speeding up the design time due to their low computational effort. In contrast, the numerical model implemented employing a finite difference method reports more details concerning the pressure distribution in the bearing recesses and land. Together with the indicated models, an analytical model for the bearing surface wear estimation was developed.

Due to the poor lubrication capabilities of cryogenic propellants and their low viscosity, the journal bearings need to be characterized in a representative pump environment. This need has implied the development of a facility to test bearings lubricated using liquid methane. Therefore, together with the design of the journal bearings, the UniPi has developed an advanced facility capable of simulating the profile of the bearing supply pressure according to the expected turbopump head during the start-up, steady-state, and shut-down operating conditions of the turbopump. Moreover, the characterization also involves representative static and dynamic loads. Finally, the facility test is intended to characterize the journal bearings under expected dynamic loads related to pump cavitation instabilities, such as rotating cavitation and asymmetric attached cavitation.

IV. Development of High-Speed Hybrid Bearing

A. Bearing Details

UniPi's propulsion team performed a survey and critical review of journal-bearing applications for turbopumps to identify the most promising candidates. Then the candidate geometries were analyzed employing the developed models, and two most promising candidate journal bearings were selected: a square-recessed journal bearing with 45° orifices (fig. 2), and a radial-orifice compensated bearing (fig. 3). Both designs have a hub inner diameter of 40 mm and are compliant with the bearing specifications reported in Table 3.

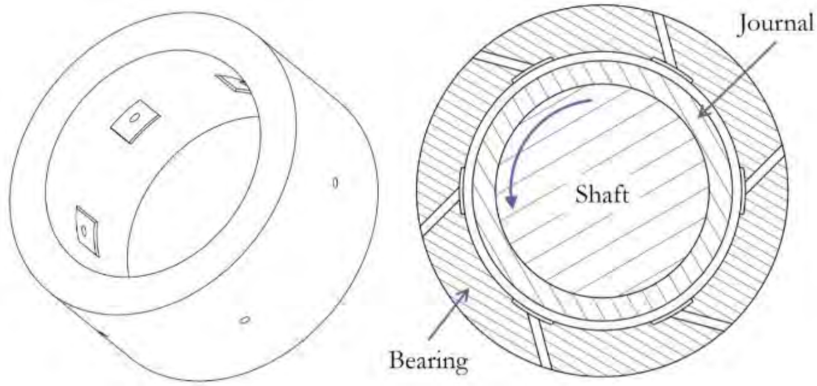


Fig. 2 Schematic view of journal bearing with 45°-orifices and squared recesses.

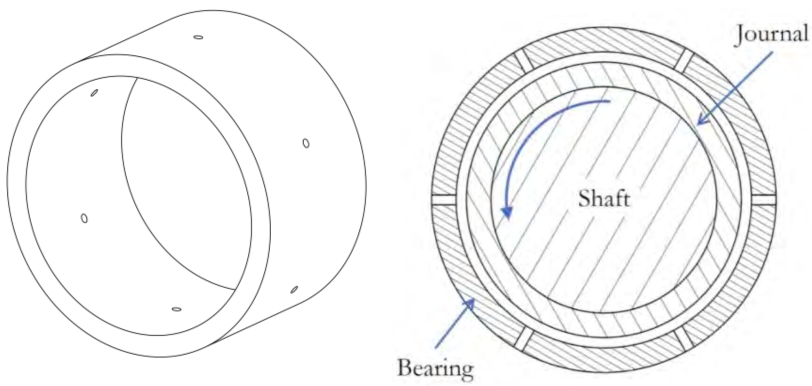


Fig. 3 Schematic view of the orifice-compensated journal bearing.

During the start-up and shut-off, the lubricant supply pressure at the bearing is low, and the lubrication could be limited or absent between the rotating shaft/journal and the fixed bearing hub. On the other hand, lubrification (LCH4) guarantees the absence of any stick-slip friction at regime operating conditions. From a tribological perspective, the start-up and shut-off are critical regimes for the surface wear of the bearing. The UniPi's team selected the most promising materials to minimize the possible surface wear of the bearings and to ensure the material compatibility with LCH4 as well as with LH2. The two most promising bulk materials are Inconel 718 and CMC, a ceramic matrix composite with carbon fibers in a silicon carbide matrix (C/SiC). The mating surfaces of the metallic solution are galvanically treated by hard coating, chromium, and soft coating, silver.

On the other hand, CMC represents an alternative solution to the metallic one due to its low friction coefficient and high wear resistance and is a promising solution compared to the sintered ceramics due to their higher resilience. UniPi selected Liquid Silicon Infiltration (LSI) for the CMC as the best compromise between technical and economic aspects.

B. Test Purpose

The project aims to assess the journal bearing durability employing a test facility capable of reproducing a representative environment of a turbopump in terms of working fluid and dynamic loads. Moreover, the bearing characterization will include the lifetime assessment of the integrity of the test items.

A large body of work dealt with journal-bearing characterization [8,17,22]. Typically, the significant parameters characterizing a journal bearing are: the stiffness matrix, the inlet-to-outlet pressure ratio, and the flow rate. As reported in [8–10], shaft speed and journal eccentricity can significantly affect the above parameters. Also, the exhaust pressure can negatively affect the bearing performance when it is low due to possible fluid cavitation occurring in the bearing land.

During the test simulating the transient regimes of the turbopump, the journal and hub of the bearing will be encountering some amount of wear. Therefore, the characterization of the material is necessary to assess the bearing reusability and collet information for possible design improvements. Indeed, the propulsion team will perform standard tests on materials and coatings (i.e. SEM, microhardness, etc.) using the laboratories of the University of Pisa. The material characterization will be performed on several items, before and after the test campaign. Moreover, the results will also indicate the most suitable material among those chosen.

Table 4 reports the test matrix defined to progressively characterize the performance of the bearings. For each test item the test campaign is characterized by different test phases:

A. General/preliminary characterization;
B. Stiffness characterization;
C. At speed characterization;
D. Start up and shut down characterization.

Table 4 Journal-Bearing Test Matrix.

Test Phase (Main Info)	Shaft Speed Ω	Supply Pressure p_s	Load Static (F_S) Dynamic (F_D)
A (Flow rate)	Different speed regime	Different supply pressure	F_S = Absent F_D = Absent
B (Stiffness)	Speed regime	Regime supply pressure	F_S = At least apply 5 different loads included the maximum value F_D = Absent
C (Bearing regime behavior)	Speed regime	Regime supply pressure	F_S = Apply the maximum static load F_D = Apply with at least three whirl frequencies
D (Bearing behavior during transient regime)	Acceleration /deceleration	From p_{start} to the regime value and vice versa	F_S = Linear relationship with the shaft speed F_D = Absent

V. Test Facility Development

A. Fluids Management System

Since the first investigations by Pratt & Whitney Aircraft Incorporated [2], the research activities have increasingly focused on the characterization of journal bearings for rocket turbopumps. The Fluids Management System (FMS) was designed to feed the journal bearings with liquid nitrogen during a set-up test phase and high-pressure liquid methane during the test campaign. The latter is available with different grades of purity. Table 5 summarizes some of the available LCH4 propellants. Liquefied natural gas (LNG) is the most common commercial mixture with methane. It was selected as the best solution for supplying simplicity, availability, and costs. The LNG is composed primarily of methane (CH4) and other hydrocarbons such as ethane (C2H6) and propane (C3H8) in lower concentrations. A very small quantity of nitrogen is also present. The reference temperature is 100 K, as it is the methane inlet temperature from the specifications (Table 3). The effect of the impurities on the methane viscosity is to increase its value due to the significant presence of ethane that has a higher viscosity. The higher viscosity is positive for the performance of the journal bearing and reduces the flow rate. There is a difference between methane Grade A and LNG dynamic viscosity of around 20%, and it remains constant in the pressure interval considered. This slight difference allows to conduct the tests with one of the two fluids and extrapolate data (scaled with the proper viscosity) without introducing significant errors. Moreover, the developed analytical and numerical models predicted that the LNG- lubricated journal bearing would fully meet the specifications reported in Table 3.

Table 5 Comparison among the pure methane, methane Grade A and LNG.

Property	Pure methane	Grade A	LNG	Units
Methane purity	100	≥ 98.7	~ 88.1	% Vol
Nitrogen N2	0	≤ 5000	~ 2298	ppmV
Ethane	0	≤ 5000	~ 116000	ppmV
Propane	0	≤ 3000	~ 251	ppmV
Vapor pressure (at T = 100 K)	0.345	0.345	0.336	bar
Density (at T = 100 K, p = 25 bar)	440.7	440.7	462.4	kg/m^3
Dynamic viscosity (at T = 100 K, p = 25 bar)	160.5	160.5	193.1	$\mu Pa \cdot s$

The fluids management system can supply LNG at variable pressure and flow rate according to the purpose of simulating the start-up and shut-off phases of a rocket turbopump. The main specifications of the fluid system are summarized in Table 5.

Due to the risks associated with a plant handling cryogenic fluids at high pressure, a significant emphasis was placed on all safety aspects during the design phase. Indeed, the plant is compliant with all the relevant Italian and European safety regulations, particularly with PED (Directive 2014/68/EU), ATEX (Directives 99/92/CE and 2014/34/UE), and Decreto Legislativo 9 Aprile 2008 n. 81.

Table 6 Specifications of the Fluids Management System.

Quantity	Range
Bearing/test item supply pressure	2 ÷ 50 bar
Bearing/test item exit pressure	1 ÷ 10 bar
Flow rate	0 ÷ 2 L/s
Maximum rise time of the supply pressure (2 to 50 bar)	2 s
Maximum drop time of the supply pressure (50 to 2 bar)	3 s
Inlet temperature of the liquid (LNG)	90 ÷ 120 K

The P&I diagram of the Fluids Management System is shown in fig. 5. LNG at low pressure is stored in the "Tank LNG" and is supplied to the "Heat Exchanger," where the liquid methane is cooled down using liquid nitrogen. Then the LNG is moved to the "Run Tank LNG," opening the valves of a cryogenic line, the "Fill Line." The LNG stored in the run tank is pressurized by nitrogen gas through the pressurizing pipeline at a value set by a pressure regulator. The pressurized LNG from the run tank feeds the journal bearing through a cryogenic line, the "Main Line." Journal bearing supply pressure is controlled by a globe valve. Another globe valve is used as a pressure regulator to control the bearing exit pressure. LNG discharged by the bearing is collected in the "Tank LNG." Boil-off gases and all safety valves are directed to blowdown stacks.

The run tank is a piston accumulator with a movable and sealed cylinder that separates the working liquid from the pressurant gas. The UniPi's team selected this solution to use an inert gas for the pressurization avoiding any possible contamination of the working fluid.

Two pneumatic-actuated globe valves are the critical components of the plants (fig. 5). The first globe valve is in the main line to precisely throttle the LNG flow rate and supply pressure to simulate any supply pressure variation in time. The second globe valve is positioned in the drain line close to the bearing exhaust pipe. This valve is used as an overflow valve to ensure constant pressure at the bearing exit. The FMS can carry out long-run tests where the supply pressure varies from the minimum to the setpoint value to assure the test requirements. The pressure is maintained constant for an extended period, and finally, it decreases to a minimum value. Thus, many start-up/shut-offs of the turbopump can be simulated employing the designed facility. Fig. 4 shows the plot of the expected supply pressure and rotational speed in function of the time required to characterize the test items.

A NI system controls the facility valves and acquires the measurements from temperature and pressure sensor located along the plant, e.g. at the exit of the run tank, immediately upstream and downstream the test item, on the fill line and drain line.

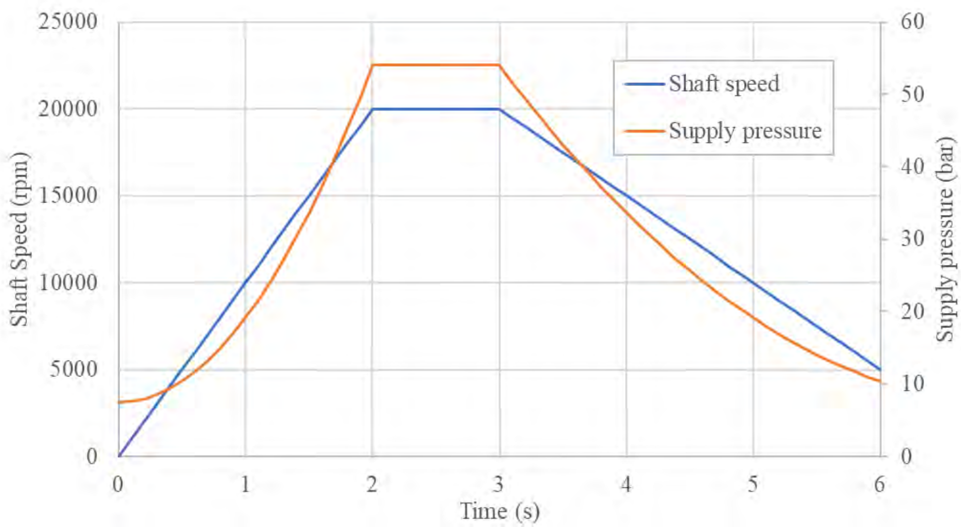


Fig. 4 Supply pressure and rotational speed during the start-up and shut-off.

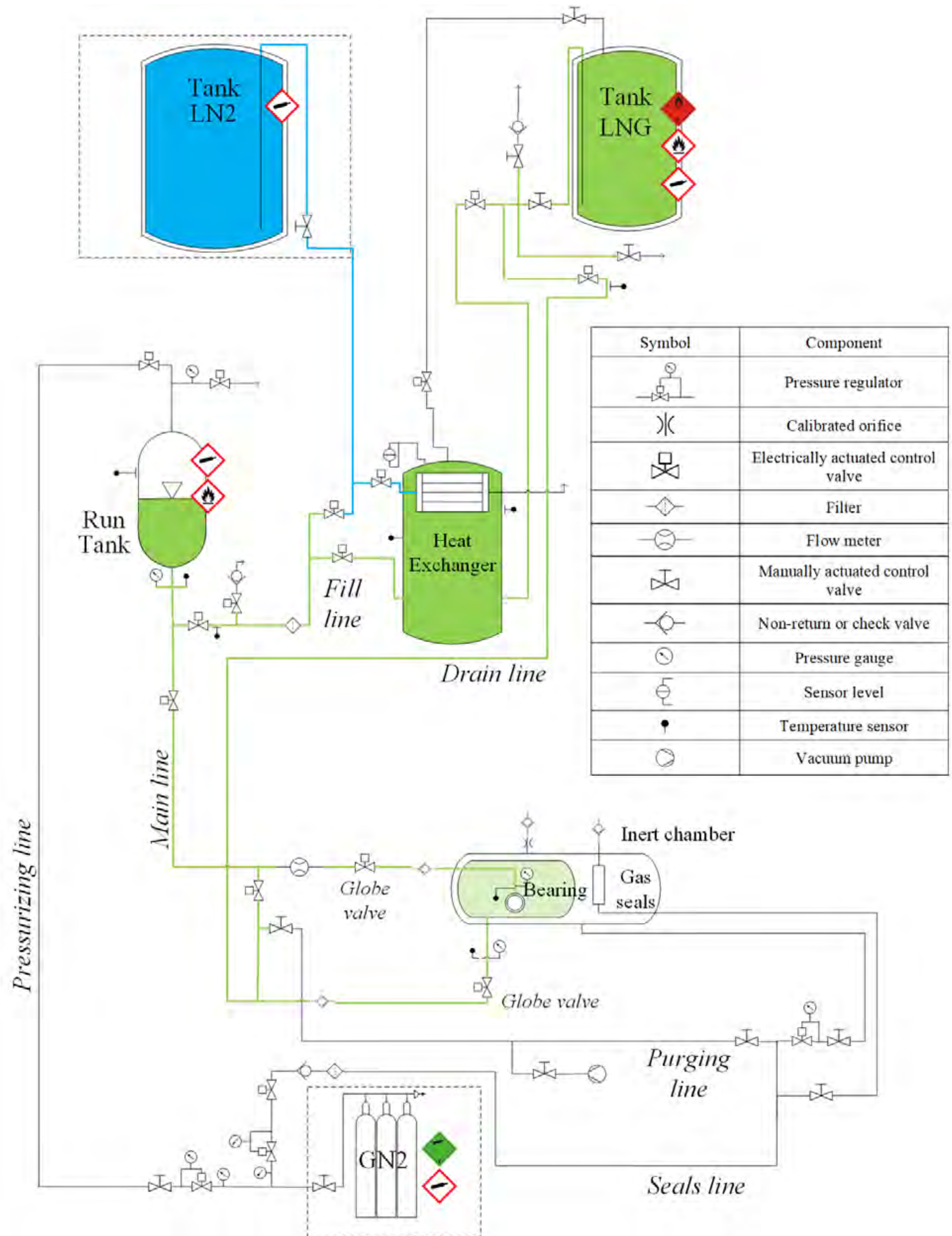


Fig. 5 P&ID of the Fluids Management System.

B. Test Rig for Bearing Characterization

The test facility reported in **Error! Reference source not found.** can be classified into two classes. The classification is related to the turbopump simulated condition. One type is focused on the characterization of journal bearing during steady-state regime with static or dynamic loads and simulation. The other simulates the turbopump conditions during start-stop transients with static or dynamic loads. Table 7 reports the UniPi's test rig specifications. The novel test rig (fig. 6) was developed to simulate both regime and transient operating conditions of journal bearings. Load values and rotating frequency depend on the test bearing performance and characteristics (i.e., mainly the permissible eccentricity and stiffness).

Table 7 Test Rig Specifications.

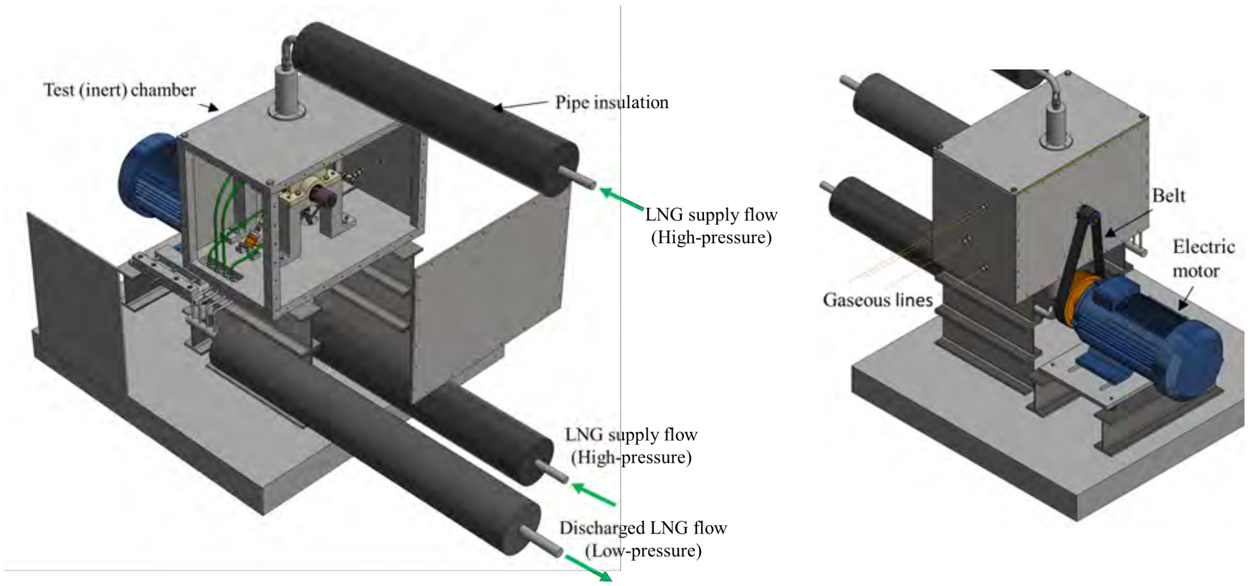
Quantity	Range
Bearing/test item inner diameter	25 ÷ 100 mm
Bearing/test item outer diameter	60 ÷ 250 mm
Bearing/test item flow rate	up to 2 l/s
Shaft rotational speed	0 ÷ 20000 rpm
Simulated turbopump start-up time	<2 s
Simulated turbopump shut-off time	<3 s
Static load	0 ÷ 2000 N
Dynamic load	0 ÷ 1000 N
Dynamic load frequency	0 ÷ 1000 Hz

The test item is mounted in the middle of a stiff shaft supported by two pairs of ball bearings (fig. 7). The seat of the ball bearings is splittable to facilitate the system assembly phases and speed up the maintenance time or the test bearing replacement. Two piezoelectric actuators apply loads directly to the test journal bearing, free in-plane movements while fixed in rotation through anti-roll arms (fig. 8). The selected piezoelectric actuators are the P-088.781 manufactured by the Physik Instrumente (PI), and their main characteristics are reported in Table 8.

Table 8 Technical specification of the P-088.781 piezoelectric actuator.

Specification	Value
Nominal travel range	70 µm (-10%/+20%)
Blocking force	7500 N
Actuator stiffness	105 MN/m
Resonant frequency	8.5 kHz (±20%)
Operating voltage	-20 V ÷ 100 V

The configuration of the actuators allows for a wide range of possible load cases, and the piezoelectric stack actuators allow very accurate positioning between rotor and bearing. Two preloaded springs ensure the contact between actuators and bearing hub during entire tests. When required, piezoelectric technology can apply a load history in the function of the shaft speed to simulate transient turbopump regimes.



(a) (b)

Fig. 6 Test Rig 3D rendering: front view (a) on the left and back view (b) on the right.

Several sensors measure the journal bearing performance (i.e., eccentricity, stiffness, pressure ratio). Two cryogenic eddy current probes measure the relative displacement between the journal and hub of the journal bearing. They are extremely precise KD2306-5UMT Kaman sensors with 1 mm full scale. The main measurement errors come from the difference between the calibration temperature and the actual operating temperature (the thermal shift is typically 0.02 %/°C). The sensor has been calibrated in liquid nitrogen at 77 K, and the actual material of the intended target has been used during the calibration.

Two high-rigidity load cells (1-CFT+/50KN by HBK) installed in series with the piezoelectric actuators detect the applied loads to the test bearing. Thus, the combination of bearing displacement and applied loads determine the bearing stiffness.

Two cryogenic pressure transducers measure the liquid pressure at the bearing inlet and exit. While four miniaturized pressure transducers (CTL-190-50 BY Kulite Semiconductor Products, Inc.) monitor the liquid methane pressure inside the bearing recesses (fig. 2) or on the bearing land in the orifice compensated bearing (fig. 3). The inaccuracy of the CTL-190 pressure transducer is ± 0.1% FSO (Full-Scale Output). This value corresponds to the typically combined non-linearity, hysteresis, and repeatability characteristics of the stated device. The full scale of the sensor is 70 bar, and the full-scale output is 100 mV (nominal values). Therefore, typical errors on the pressure measurements are of ± 0.07 bar (±0.1 mV) at full scale. These sensors will be used to detect possible flow instability or cavitation for a detailed characterization of the bearings. The temperature measurements are collected with the data of several T thermocouples arranged in the bearing housing and on the test rig.

The test rig has been developed to be compliant with ATEX (Directives 99/92/CE and 2014/34/UE) and designed to handle cryogenic temperatures. Moreover, a constant flow rate of nitrogen gas is injected inside the test rig chamber to obtain an oxygen concentration less than the limiting oxygen concentration of 11%. The control system and data acquisition system will be performed by a CompactRIO (NI) controller located in a safety cabinet.

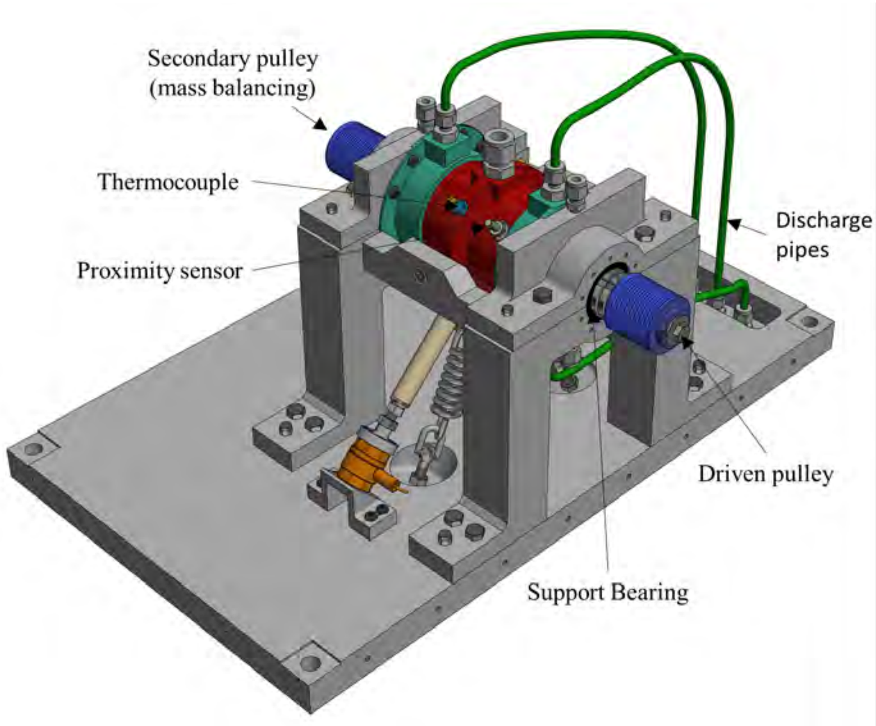


Fig. 7 Details of the Test Rig (3D rendering).

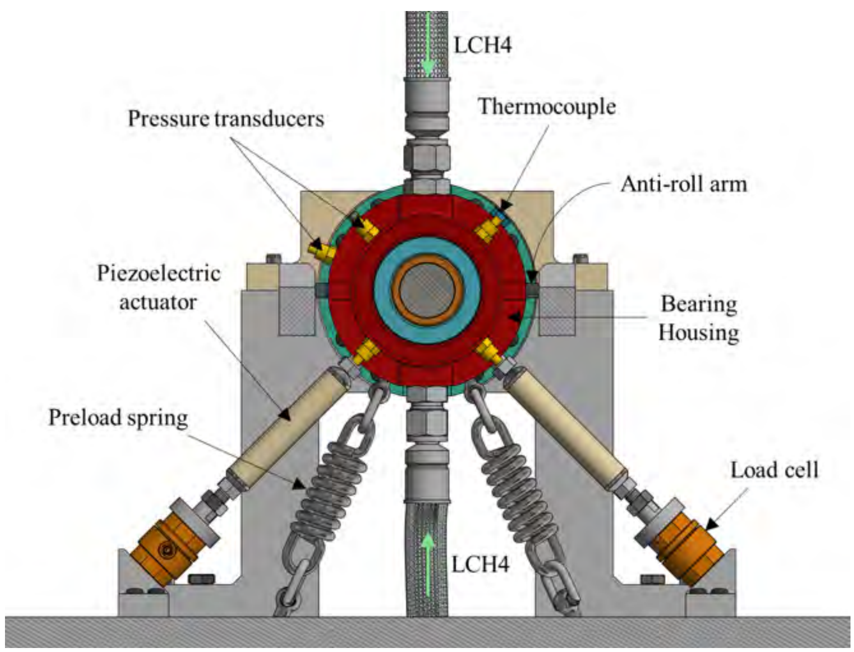


Fig. 8 Schematic representation of the Test Rig.

VI. Conclusions

The turbopump bearings have been identified as the critical technology to improve the lifetime truly reusable liquid rocket engines. The propulsion team of the University of Pisa selected high-speed journal bearings as the most promising technology for first-stage liquid rocket turbopumps. In particular, the development of such technology for liquid methane results in particular interest because LOX/LCH4 is a candidate for the next generation of reusable launch vehicles.

The paper reports the identification of journal-bearing requirements for a first-stage turbopump with shaft power in the range of 2.4 MW. The paper outlines the design of two candidate geometries of high-speed journal bearing and presents the development of a novel test rig suitably designed for investigating static and dynamic characteristics of high-speed journal bearings employing LCH4 and replicating a turbopump environment.

The novel test rig for the bearing performance assessment has unique features:

- the compatibility with LNG/LCH4 (and LN2 without any modification and easily extendable to other cryogenic fluids);
- the possibility of performing with the same set-up both steady-state tests and transient start-up/shut-off cycles;
- the possibility of introducing unsteady loads capable of also simulating the typical forces produced by cavitation-induced instabilities using piezoelectric actuators.

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