

Liquid Hydrogen Supported Foil Bearings for Launch Vehicle Propellant Densification

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Abstract. Launch vehicle propellants can be densified by an external thermodynamic vent principle operating sub-atmospheric pressure and benefits the space launch industry by reducing vehicle gross lift-off weight (1). However, this principle requires compressors to generate significant head (0.1 bara inlet to 1.1 bara discharge for hydrogen) which can either be achieved by high shaft speed or by multiple compression stages. Traditional propellant densification systems utilize compressors with grease packed ball bearings which limit shaft speed thereby driving the system design toward multiple compression stages and greater complexity while also shortening service intervals. In association with a NASA Small Business Innovative Research (SBIR) initiative to improve this process, Barber-Nichols Inc. (BNI) developed and tested liquid hydrogen lubricated foil bearings in a high-speed hydrogen gas compressor for the production of densified launch vehicle propellants. Foil bearings do not have the same shaft speed limitations allowing the compressor to run faster reducing the number of compression stages and simplifying the propellant densification system. The test results are presented here.

1. Introduction

The use of foil bearings for turbomachinery applications is not new. Some of the fielded applications using foil bearing technology include aircraft air-cycle machines and industrial blowers for waste water treatment plants. Utilizing foil bearings for use in turbomachinery for the cryogenic field is fairly uncommon, but has been supplied for gaseous helium (2) and hydrogen applications (3). Unique to the Barber-Nichols hydrogen compressor is the use of liquid hydrogen supply to the foil bearings coupled with the relatively large compressor power and shaft speed.

As is common in NASA SBIR work, this compressor design and testing consisted of several work elements that were performed

- Preliminary design and analysis for the foil bearing hydrogen compressor
- Modification of a commercial machine
- Bearing testing on liquid hydrogen
- Modification of the machine for hydrogen compression testing using commercial compressor impellers.

2. Preliminary Design and Testing

To prove the efficacy of a cryogenic liquid foil bearing compressor application, a project was undertaken to modify an existing commercial foil bearing machine. Early studies identified the configuration, power, and shaft speed requirements for a 2 stage hydrogen compressor. This closely matched one of several commercial air compressors that had been designed by Barber-Nichols for a private customer. The design knowledge of the selected commercial compressor was then used for this initial analytical, design, and test exercise. A four step process advocated by NASA for foil bearing implementation into turbomachinery was used for the commercial machine design and was reintroduced for the modification of the machine for cryogenic use.

2.1. Preliminary design and analysis for the foil bearing hydrogen compressor

The first step in the 4 step process is a bearing design and rotordynamic study. As mentioned previously, the machine was designed by Barber-Nichols for use on air as the bearing support fluid. A preliminary machine layout, figure 1, provides the rotor size and weight that is used for the bearing design. A “rule of thumb” approach (4) coupled with a preliminary journal bearing performance map technique (5) is then used to estimate the required bearing size where the modified Sommerfeld number versus specific power loss plot is used as guidance. It is clear that a modified Sommerfeld number of 6 is required for successful foil bearing operation. Also shown in figure 1 is the final tested commercial machine configuration.

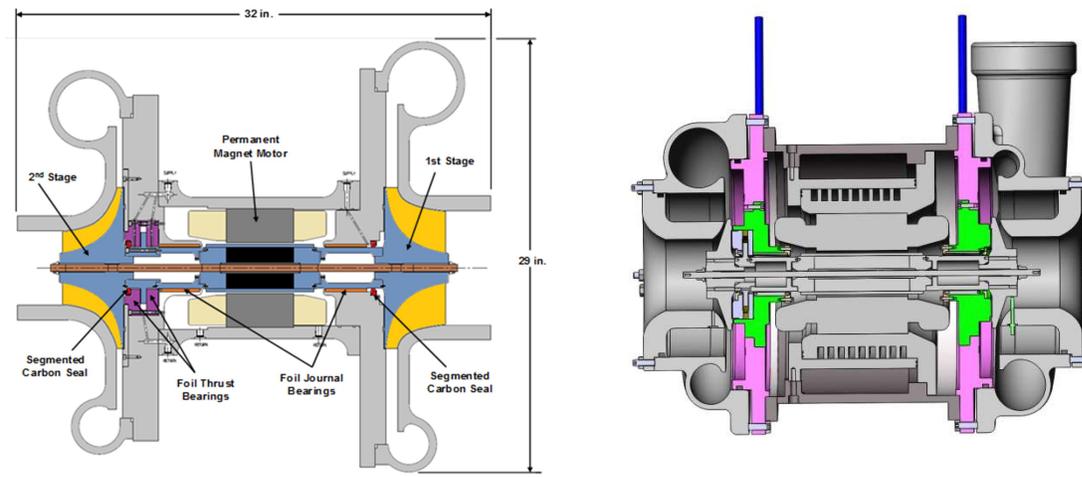


Figure 1. Preliminary and final cross section of the 2-stage foil bearing machines

2.2. Foil bearing design

The radial bearing design was conducted based on use of XL2DGFB software developed by Texas A&M, Barber-Nichols foil bearing experience to date, and reference 3 (NASA). Barber-Nichols' experience to date includes foil bearings for shaft diameters ranging from 30mm-80mm with air and carbon dioxide as the working fluid. The proposed working fluid is LH2 with viscosity of .013 cPoise and density of 4.4 lb/ft³. Viscosity is the primary property determining bearing load capacity and in this case is similar to air at standard conditions (.018 cPoise). Therefore, bearing design has been performed utilizing similar

criteria for bearings operating in air. LH2 density is significantly higher than air and must be considered for windage losses.

Key bearing design criteria are listed below and were utilized to design the bump foil structure. The stiffness range is based on empirical data and rule of thumb recommended by NASA. The modified Sommerfeld number is a dimensionless parameter characterizing bearing performance. It allows for bearing scaling based on viscosity, bearing diameter, speed, and performance coefficient. The minimum modified Sommerfeld number listed below is based on operation in a thermally stable region for foil bearings as determined by NASA testing.

- Stiffness: 2500 - 7500 lb/in²/in
- Modified Sommerfeld Number > 6

A foil bearing diameter of 70mm was determined during the previously described rotordynamic trade study utilizing the above Sommerfeld number constraint. A length of 70mm or length / diameter equal to one was then chosen based on prior experience. Figure 3 of modified Sommerfeld number vs speed was made utilizing this geometry and LH2 properties. The curves corresponding to liquid and gaseous hydrogen represent the expected extremes as some two phase flow in the bearings will be possible. A key takeaway is that an effective viscosity midway between the liquid and gas values will yield sufficient bearing performance (ie modified Sommerfeld number > 6). The gaseous nitrogen curve is plotted to confirm that cold gaseous nitrogen can serve as an effective test medium.

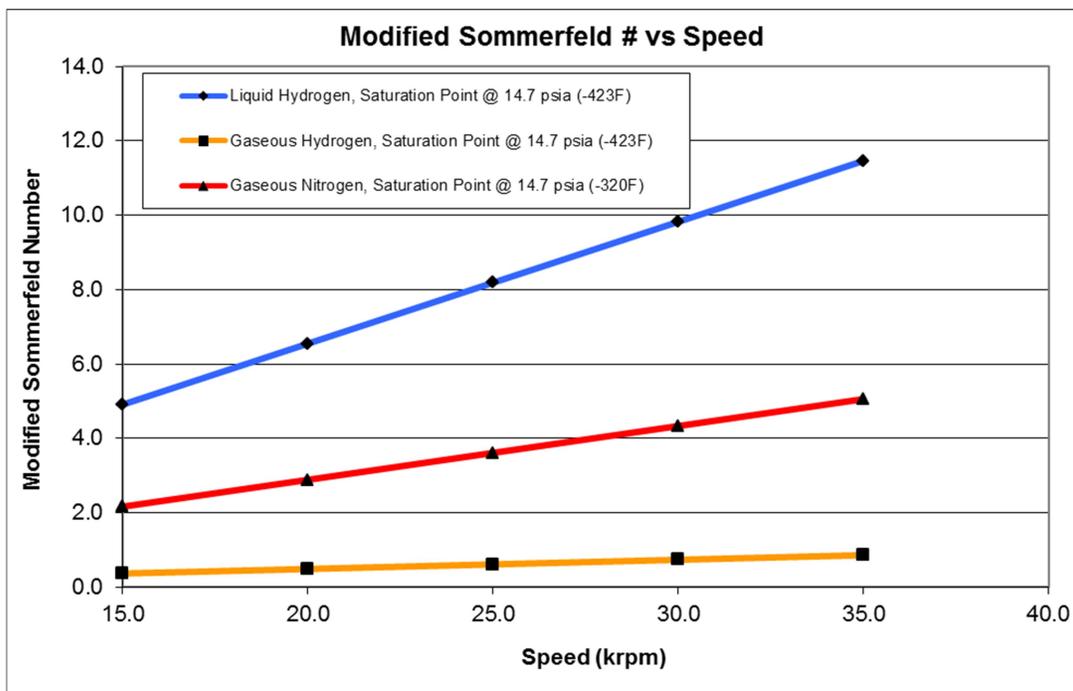


Figure 3. Speed versus Modified Sommerfeld Number for Nitrogen and Hydrogen

2.3. Preliminary rotordynamic analysis

A rotordynamic trade study was conducted as part of the NASA four step process for development of foil bearing machines. A number of design considerations and constraints were utilized to arrive at the preliminary rotor design.

A critical speed analysis is performed and summarized by the undamped critical speed map in figure 4. The blue box represents stiffness uncertainty and the margin requirement of +/-20% above and below the operating speed. Operation occurs between the 2nd and 3rd critical speeds as typical for foil bearing systems. The first two critical speeds are determined primarily by rotor mass and bearing stiffness. Typically these modes are traversed quickly during start up to minimize imbalance response. Large critical speed margin above the 2nd critical allows for high uncertainty in the bearing stiffness characteristics. The above analysis ensures acceptable imbalance response is feasible.

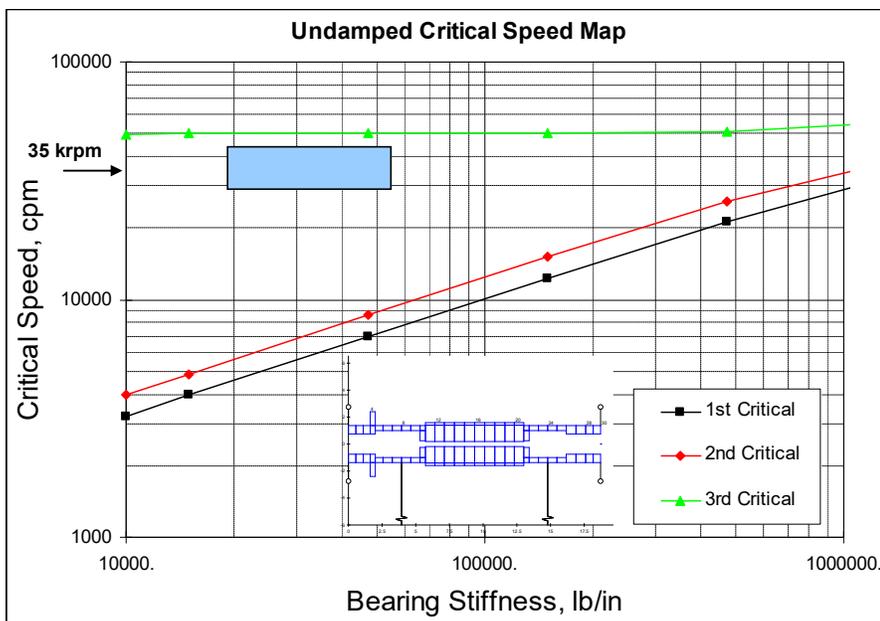


Figure 4. Undamped Critical Speed Map

2.4. Foil Bearing Testing

The foil bearing testing included individual bearing testing on air, and cryogenic testing on hydrogen with a full rotor mock up. Ideally, individual journal bearing testing on liquid hydrogen would be performed, but due to funding level and schedule it was elected to proceed directly to full rotor testing.

The first step was to test the journal bearings individual on air in a journal bearing test fixture. This fixture enabled testing for load, speed, and power loss. It also enabled the confirmation of the lift off characteristics to confirm the Sommerfeld number information was as analysed, figure 5.

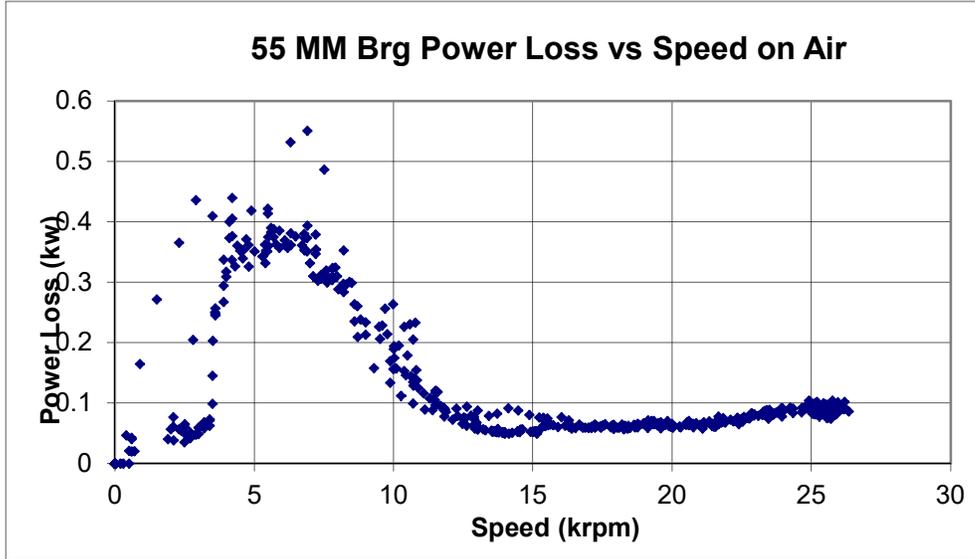


Figure 5. Journal bearing shaft speed versus bearing loss on air

3. Modification of a commercial machine

The design of a 2 stage compressor was done with the foresight of an available commercial machine suitable for modification to cryogenic use. The commercial machine cross section solid model shown in figure 1 was not designed with any sealing arrangement to contain hydrogen so the entire machine was placed into a tank that would maintain a hydrogen boundary for both the liquid and the gas phases. The use of a tank also allowed easier application of insulation. The rotating machine installed in the pressure boundary tank and the rotor parts are shown in figure 6 (some piping removed for clarity). Entering from the top of the tank is the liquid hydrogen feed, pressure sensors, liquid level sensors, proximity sensors, and temperature sensors. The commercial machine had endplates which were modified for the introduction of liquid hydrogen directly into the bearing. The tank bottom incorporated a liquid drain for the excess hydrogen that escaped from the seals. This liquid went into an evaporator prior to being expelled to the atmosphere during test.



Figure 6. Machine in pressure safety tank and rotor/bearing parts

4. Foil bearing testing on liquid hydrogen

To test the bearings on liquid hydrogen is the 3rd step in the 4 step process. To perform this test, the bladed wheels were removed and surrogate smooth disks were installed. These disks had the same mass properties as the bladed compressor components.

Due to the expense of liquid hydrogen, the goal of the test was limited to multiple starts and stops while operating the rotor to 18,000 rpm and letting the rotor coast to a stop. This is an indication that the bearings could support the rotor and also insure that the hydrodynamic lift off speed was achieved. It is important to know the lift off speed when operating the compressor. A lower starting compressor test operating speed is advantageous to minimize risk when operating the machine at higher power.

The compressor tank was placed onto a frame where tank insulation was applied and then protected with an aluminium skin box. This was placed into the test setup where wiring, plumbing, helium purge system, electrically operated valve, and a gaseous hydrogen exit chimney were installed. The test was performed at IES in Murietta, California, US using a 13,000 gallon vacuum jacketed liquid hydrogen tank. The bearing flow was modulated by pressurizing the tank and using a flow control valve. The location does not allow burning the exhausted hydrogen, so it was discharged into the atmosphere. Figure 7 shows the compressor installed in the insulator box and the discharge chimney with the electrically operated valve.



Figure 7. Bearing Test Apparatus Installed at Test Site

The bearing testing encompassed eight start stop cycles with various running durations. The maximum operational speed was 22krpm with most data taken at 18krpm where the shaft was operated for approximately 30 seconds each time. The lift off speed was verified by coast down information.

5. Compressor Testing

After verification of the hydrogen liquid fed bearing operation, the machine and test configuration was modified for compressor testing. Compressor wheels designed for the air blower were installed on the rotating machine as funding was not available to manufacture and install the compressor wheels design for the hydrogen conditions. The lower predicted performance wheels allowed the use of a 1600 gallon vacuum jacketed tank to serve as a cold vapor source for the hydrogen compressor. The 13,000 gallon liquid tank was still used to provide cold liquid hydrogen bearing flow. Several electrically operated isolation valves were installed to provide system purge, and pressurization capability. The 1600 gallon tank was filled warm on the morning of the test to approximately 1000 gallons. The pipe from the tank to the compressor was left un-insulated to provide extra heat transfer to warm the hydrogen and minimize the possibility of liquid hydrogen boil off entering the compressor inlet. Figure 8 shows the compressor test equipment photograph.

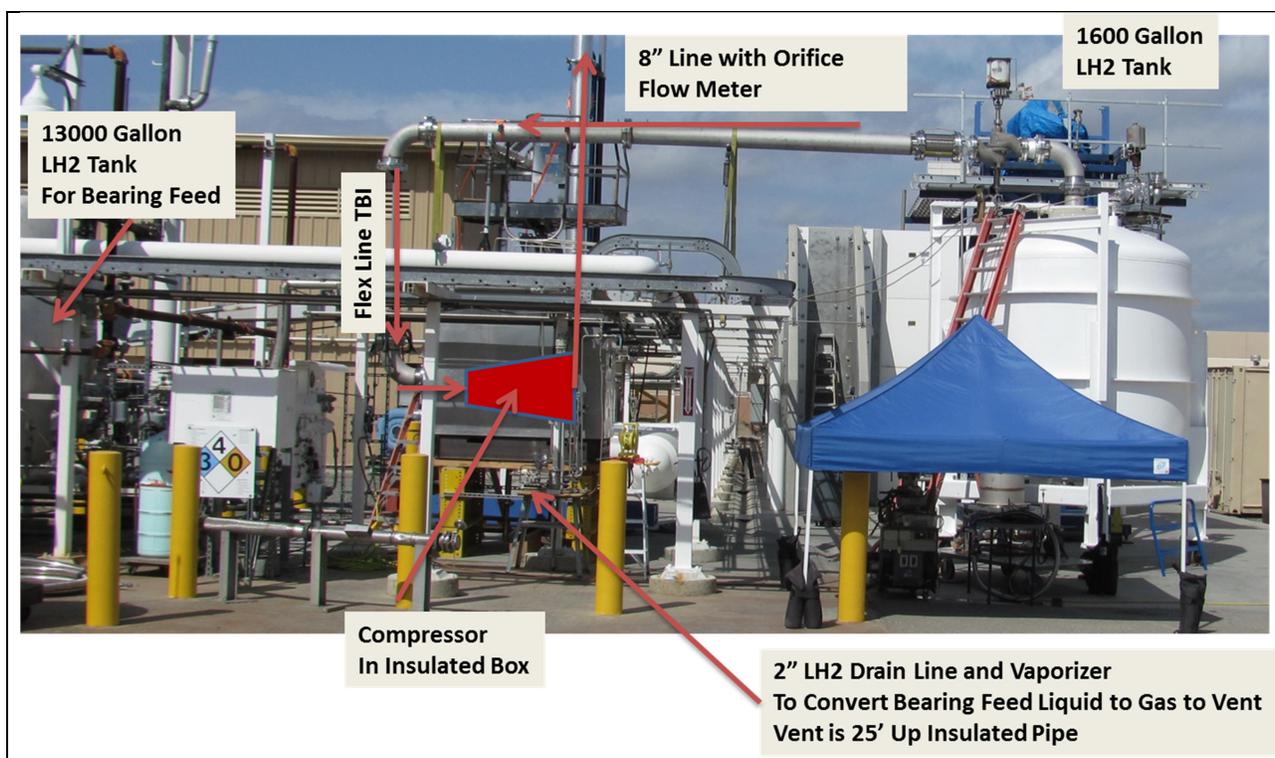


Figure 8. Compressor Test Arrangement

Four compressor tests were performed. The initial tests were used for operation and instrumentation checkout. The final test culminated in a maximum shaft speed of 35,000 rpm. A plot of the shaft speed vs pressures is shown in figure 9.

6. Conclusion

It can be seen that the compressor was successful in pulling the hydrogen pressure lower in the ullage tank. Upon machine inspection, the compressor parts were in good condition. The next steps for the machine is to manufacture the proper hydrogen compressor impellers and devise a performance test.

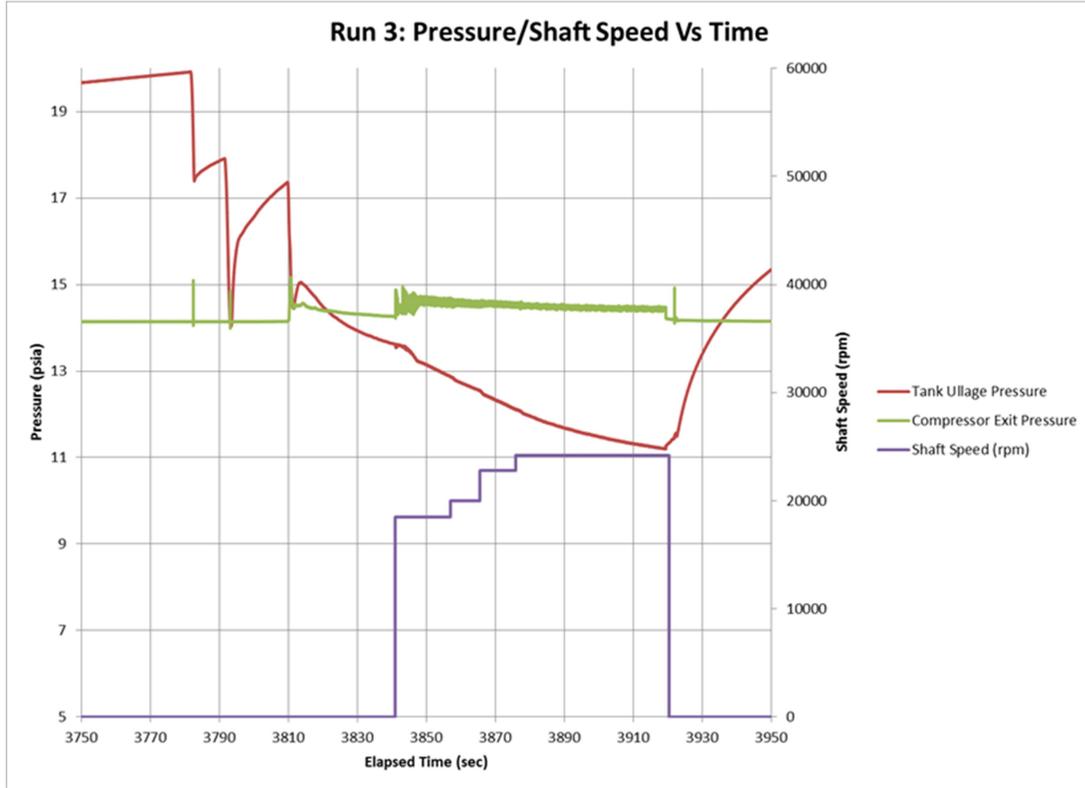


Figure 9. Time versus shaft speed and inlet/outlet pressures

7. References

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Acknowledgments

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