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Experimental validation of a thermal model of a LOx flooded ball bearing

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ABSTRACT

Ball bearings of turbopumps of rocket engines work in very singular conditions; they are flooded into liquid oxygen or liquid hydrogen. Therefore, the use of any conventional lubricants (oil or grease) is prescribed. Although cryogenic fluids can cool this kind of ball bearing, they cannot separate the surfaces in contact. As a result, there is a significant increase in frictional power losses. This paper presents tests performed on a cryotechnic ball bearing flooded in liquid oxygen. The test results showed that beyond a critical loading of the bearing, a sudden increase in temperature occurred. A thermal model is also put forward, in order to understand and anticipate especially the thermal instability described above.

1. Introduction

Despite an apparent simple geometry, cryotechnic ball bearings hide several phenomena that are difficult to identify. These particular ball bearings make up an essential part of turbopumps of rocket engines. They are flooded into liquid oxygen or liquid hydrogen and also subjected to high forces and high rotational speed.

Cryogenic fluids do not allow the use of conventional lubricants as oil or grease. They correctly cool the ball bearing but there is no thin elastohydrodynamic film separating the surfaces as a consequence of their low viscosity. Besides, the lubrication regime is equivalent to a dry one [1]. The friction forces induced by the lack of conventional lubricant imply a significant heat generation at ball/race contacts.

With regard to tests performed on cryotechnic ball bearings flooded into liquid oxygen, the present study establishes that a sudden increase in the bearing temperature is observed when the friction level is too high. This can lead to the destruction of the ball bearing. A thermal model is also proposed to understand the phenomenon and anticipate especially this sudden increase in temperature.

2. Ball bearing tests

2.1. Test bench

The Laboratory of Industrial Chemistry of University of Liège reproduced the operating conditions of a deep groove cryotechnic ball bearing flooded into liquid oxygen (LOx) [2]. A test rig was designed and manufactured by the laboratory. Tests were realized for a range of several parameters (axial and/or radial loading, clearance, coating on grooves, liquid oxygen mass flow rate, etc.).

A cutaway of the test bench is presented in Fig. 1. The set of the different measurements available on test rig is also included. Some items from this list can be pointed out: the inner and outer rings' thermocouples, the temperature and pressure measurements of the liquid oxygen flowing through the bearing, the measurements of the shaft rotational speed and of the forces applied to the bearing. The two inner ring temperature thermocouples, which were extremely difficult to install on the rig, constitute one of the original features of the test bench. Those measurements were made by using two thermocouples diametrically opposed for redundancy purposes.

2.2. Thermal divergence

Some of the tests realized on the test rig were performed with uncoated all-steel deep groove ball bearing, which has a fixed diametral clearance and a bore diameter smaller than 50 mm.

Under high loadings, all the thermocouples recorded some sudden thermal increases in temperature. The tests involved are

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W1:	electrical motor power
V1, V2:	rotational speeds of the motor shaft and of the tested bearing shaft
F1, F2:	axial and radial loads
I1, I2:	axial and radial displacements
A1, A2:	axial and radial accelerations
ΔP:	LOx differential pressure (subtraction of the upstream pressure from the downstream one of the tested bearing)
P1:	tested bearing upstream pressure
T1, T3:	cup temperature
T2, T5:	upstream and downstream temperatures of the tested bearing
T4:	outer ring temperature (X3) of the tested bearing
T6, T7:	inner ring temperatures of the tested bearing
T8 to T11:	outer ring temperatures of the housing bearings
T12, T13, T15, T16:	housing temperatures
T14, P2:	temperature and pressure of the lubricant (housing)

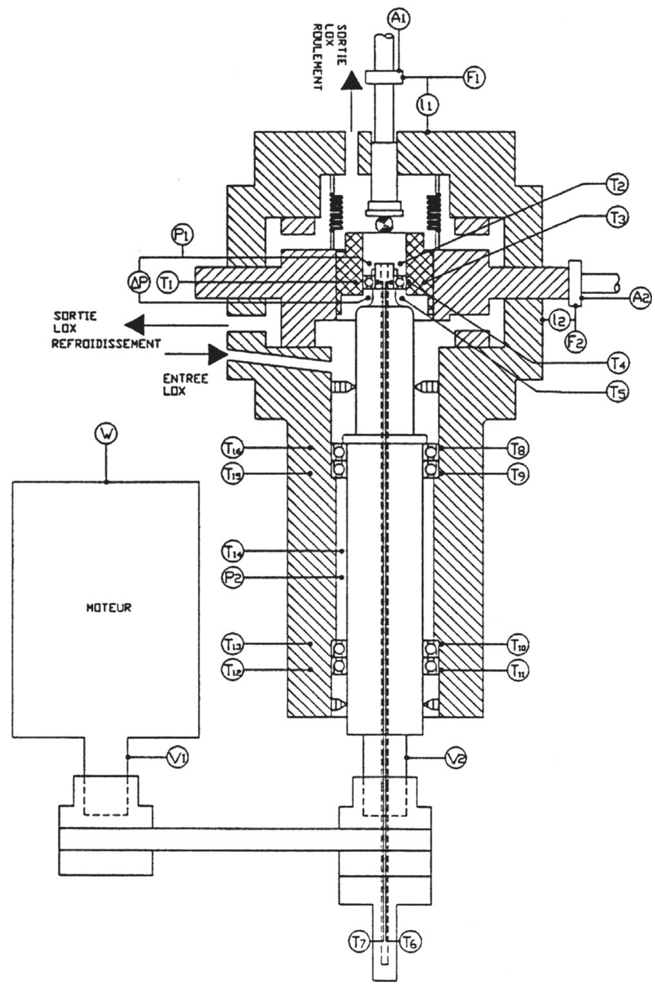

Fig. 1. Cutaway of the cryotechnic ball bearing test bench.

Table 1
Operating conditions for tests showing sudden thermal divergences.

Test number	F_a (daN)	ω_I (rpm)	p_{LOx} (bar)	$\dot{m}_{LOx}$ (bar)	T_{sat} (K)	T_{BI} (K)
Test 1	245	14,000	12.5	25	123.6	125.5
Test 2	250	14,000	7.4	25	114.7	117
Test 3	310	13,000	12.7	25	123.9	118
Test 4	280	14,000	12.8	42	124	121.5
Test 5	310	14,000	12.8	43	124.1	116
Test 6	264	14,000	12.7	25	123.8	121.8
Test 7	297	14,000	12.9	43	124.1	113.6

summarized in Table 1. This table contains the loading applied to the inner ring (F_a), exclusively axial, the inner ring rotational speed (ω_I), the liquid oxygen pressure around the ball bearing (p_{LOx}), the mass flow rate of the liquid oxygen ($\dot{m}_{LOx}$), its saturation temperature (T_{sat}) and the measurement of the inner ring temperature (T_{BI}).

An example of sudden increase in temperature (thermal divergence) is depicted in Fig. 2, for the test number 5. The curves represent the axial load sensor measurement and the temperatures given by both inner ring thermocouples. As the figure shows, a thermal divergence happened more or less 1005 s after the beginning of the test and for an axial loading of 310 daN.

Before this thermal divergence occurred, bulk temperatures recorded by the test bench remained constant independent of the loading imposed, thus independent of the power dissipated by friction (see Fig. 2, from 0 to 1005 s). This conclusion generalizes to other test results. Moreover, all the recorded temperatures remain unchanged (to some degrees) for fixed liquid oxygen characteristics (mass flow rate and temperature) and inner ring rotational speed.

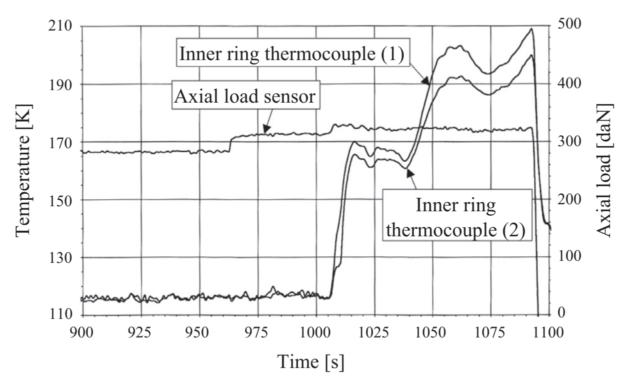

Fig. 2. Example of sudden thermal divergence, observed by using the inner ring thermocouples.

Such a thermal instability is clearly due to a quick variation in convective heat transfer into the ball bearing, which leads to a large decrease in heat evacuated by the liquid oxygen. Indeed, the power dissipated into the ball/race contacts is caused by friction between tiny surfaces. This implies a significative rise in temperature in the vicinity of ball/race contacts. Therefore, it is believed that thermal divergences are the result of the phase transition of the liquid oxygen in the zone surrounding the