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THE BEARING SYSTEM FOR THE CALIBRATOR OF SCHENBERG DETECTOR

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ABSTRACT
This paper presents some topics for the "Mario Schenberg" gravitational waves detector calibrator, focused on the bearing system. This device must symmetrically rotate two objects, with mass and at a radius as large as possible, at a speed of 96,000 rpm, and therefore falls into the high-speed machines category. The guidelines and solutions proposed in this paper constitute a contribution to this class of engineering problems and were based on an extensive literature search, contacts with experts, the tutor's and author's experience, as well as on experimental results. A hybrid bearing that combines a radial passive magnetic bearing with an axial sliding bearing, here called MPS (Magnetic Passive and Sliding, was proposed. A reduced physical prototype was built and tested. Although the prototype has been tested at speeds below 12,000 rpm, the proposed guidelines were partially validated.

Keywords: Gravitational Waves Calibrator, Mario Schenberg Detector, High Rotation Machine, Passive Magnetic Bearing, Magnetic Sliding Bearing..

INTRODUCTION

Since Einstein's prediction of gravitational waves in 1916, scientists around the world are attempting to detect it, first signal were found. There are few gravitational wave detectors in the world. Brazil participates in this international effort with its resonant mass detector called "Mario Schenberg", built by the research group Graviton and installed at the University of São Paulo. To carry out the calibration of the Mario Schenberg detector an external device is necessary (Calibrator) capable of generating a periodic tidal signal. This device, here designated by the acronym DCMS (Device for Calibration of the Mario Schenberg detector), should rotate symmetrically two equal objects with the largest mass and at the largest possible radius, at a frequency of 1,600 Hz or 96,000 rpm (ANDRADE , 2006; PADOVANI, 2012; RUIZ, 2014; SANTOS, 2013). Figure 1 shows a basic schematic of this device.

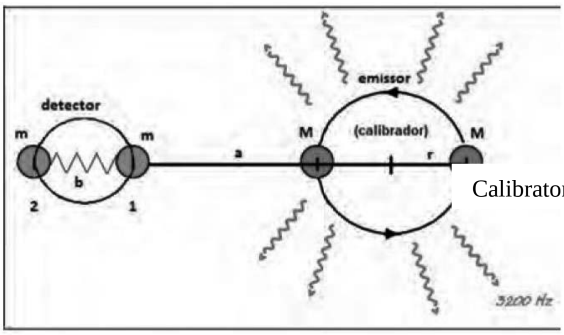

Fig. 1 Schematic illustration of the gravitational signal generator Source: Adapted from Padovani (2012).

The DCMS fits into the well-known class of engineering problems called "High Speed Rotary Machines High Speed " (WATSON, 1999). The project and the manufacture of these machines bring important challenges that involve several areas of Engineering.

According to Choi (2015), such problems include mechanical, electrical and magnetic losses, extreme mechanical stresses arising from high centrifugal forces, heating, power limitations of electronic circuits, increasing complexity of control algorithms and complex linked issues to the dynamics of rotors and vibrations.

The present work is part of a broader study aimed at obtaining guidelines for the whole project of the

DCMS (FERNANDES, 2015). In this preliminary work the main challenges to be overcome for the construction of such a device were discussed. This involved studies related to:
A) Protection structure: To ensure protection against the risks inherent in high speeds and at the same time eliminate aerodynamic drag, it was proposed to operate the DCMS inside a vacuum chamber shielded with ballistic materials;
B) Bearing: After careful comparative studies among several types of bearings presented in the literature, the hybrid passive magnet permanent magnet model developed in Pavani (2014) was adopted;
C) Design of the rotor: In order to withstand the high centrifugal load resulting from the high rotations, a system has been proposed for curing the rotating objects with carbon fiber, supported by a disc-shaped structure made of a composite of carbon fiber in epoxy resin;
D) Drive: It was proposed direct drive of the rotor (direct drive) with a reluctance motor controlled by an advanced electronic control algorithm;
E) Rotor Dynamics: Important guidelines have been proposed to avoid, or at least mitigate, the vibrations that cause instabilities in the rotor and often prevent the reach of high speeds.

MATERIALS AND METHODS

Selection of bearing type: The selection of bearings is generally focused on reducing the energy losses due to friction and wear, thus minimizing maintenance, increasing life and reducing equipment failure (HARNOY, 2003 apud PAVANI, 2014).
Among the most critical challenges encountered in the construction of the DCMS is the development of a DCMS high-speed rolling bearing that exhibits the least possible mechanical loss and rigidity sufficient to maintain the stability of the rotor, which is capable of attenuating vibrations, constructive and operational simplicity, among other requirements.
According to Pereira (2005), it is desirable in any rotary machine that the bearings be more flexible than the rotor shaft. The reasons for this are:
A) The low stiffness of the bearings reduces the transmission of the dynamic loads to its foundation, Service life of bearings and reducing structural vibrations;
B) Low bearing rigidity allows damping to operate more efficiently, attenuating the rotor's amplitude at critical speeds.
According to Borisavljevic (2011), in addition to operating practically without friction, the magnetic bearings operation, at extremely high speeds, and have the ability of the suspended rotor to rotate around its center of mass and not necessarily around its geometric center, thus allowing a rotor and high speed range. Whitley (1984) confirms that, in order for the rotor to benefit from a more flexible bearing system, such as magnetic bearings.
After careful analysis of the advantages and disadvantages presented by the different types of bearings, it was concluded that magnetic bearings are best suited for the high speed required by DCMS.
In Ruiz (2014) a study on the DCMS was carried out, recommending the use of magnetic bearings with variable reluctance drive which, according to Lembke, 2005, would have the following advantages:
- High reliability;
- Low losses, even at very high speeds;
- No wear, since there is no mechanical contact between the bearing parts;
- Absence of acoustic and vibrational noise;
- Greater simplicity when compared to active magnetic bearings;
- Report of tested bearings in vacuum pumps with speeds above 90000 rpm.

Permanent magnet passive magnet bearings (PMPMs) exhibit the most extreme simplicity, reliability and durability, requiring no supplies of external energy (YONNET, 1978), nor cooling systems for its operation. Considering its simplicity, PMPM was chosen. However, PMPMs need stabilization in at least one direction (EARNSHAW, 1842). This often requires the use of complex active systems.
The MPS (Magnetic Passive and Sliding) bearing: Pavani (2014) presents a simpler strategy for the axial stabilization of an MMP. The MMP proposed by the authors is intended for applications where axial forces are very small or constant, as in the case of DCMS. This bearing combines a radial MMP and an axial sliding bearing (strut) by pivots. The radial MMP consists of two pairs of cylindrical permanent magnets in axial attraction. In each pair, one of the magnets is attached to the end of the shaft

and the other to a fixed base. The rotor is self-centered in the radial direction by the action of the attraction between the magnets of each pair. Due to the negative rigidity in axial direction, the proposed bearing contains a spacer (steel ball or PVC pivot) between the magnets. By adjusting the spacing between the magnets, it is possible to minimize the axial force resulting from the attraction of the two bearings. According to the authors, the lower the resultant force, the lower the friction losses and the wear of the surfaces in contact (Figure 2).
This bearing, here called the MPS (Magnetic Passive and Sliding), presents a number of advantageous features for the DCMS, such as extremely constructive and operational simplicity, compact dimensions, no maintenance, very low friction, durability and reliability, this hybrid bearing concept was adopted for DCMS.
Magnetic bearings and brushless motors: The advantages of the use of brushless electric motors and magnetic bearings at high speeds. However, these two solutions implies an important challenge. As explained in RUIZ, 2014, the rotor / stator air gap should be as small as possible to ensure the efficiency of an electric motor. On the other hand, if the rotor is suspended by a PMPM, the rotor can move from its axis of rotation when facing vibrations and other instabilities (LI, 2012).
The engine air gap designed in Ruiz (2014) was specified in 0.25 mm, however the smallest one obtained in the experiments of this work was 0.75 mm, due to the collisions of the rotor with the stator.
The landing bearings: The limited rigidity of magnetic bearings requires the use of auxiliary landing bearings intended to contain temporary rotor oscillations within the limit established by the radial clearance (Figure 2). These bearings can be constructed with ball bearings ceramic elements (hybrids). Cage bearings are not recommended because of their lower resistance to repeated shocks with the rotor (KÄRKKÄINEN, 2007). Figure 2 shows the application of the emergency bearings.

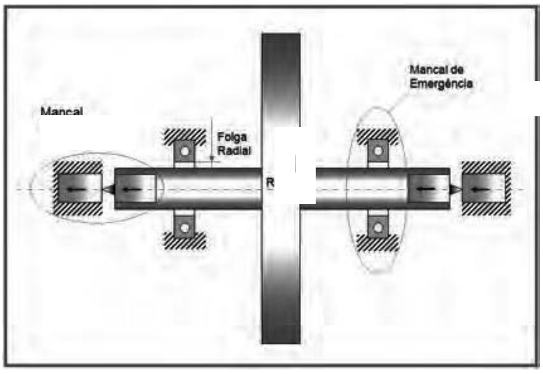

Fig. 2 joint bearings emergency bearings with the MPS bearings

According to Halminen et al. (2015), it is recommended a good alignment between the bearings, since large misalignment may cause serious damage to the bearings and to the rotor. Since DCMS should operate in a vacuum, the bearings must be lubricated with lubricants such as, for example, those made on the basis of Fluorinated polymers, including polytetrafluoroethylene (PTFE) known commercially as Teflon (NISHIMURA, 1999).

RESULTS AND DISCUSSIONS

In order to confirm the feasibility of obtaining a DCMS with the use of the above MPS bearing described, as well as identifying the various problems to overcome in order to obtain the DCMS, a prototype was built containing a rotor supported by bearings MPS and an electric motor for its drive.
At this stage of the research, it was not 96,000 rpm, specified for the DCMS.
The bearings: Two identical MPS bearings were constructed with based on the principle presented in Pavani (2014). Each two cylindrical magnets ($Nd_2Fe_{14}B$, Ø14x14 mm) in axial attraction, and a polymer pivot (PVC), the centralizing device provides greater ease and speed in replacing of the pivots.
The Bearing bases allow easy installation and removal of magnets and adjustment of the distance between bearings, which allows you to adjust the air gap in the bearings. Per ease of construction they were implemented in wood.

The drive: The drive of the rotor was made by a variable reluctance type motor consisting of a single-piece core made of sweet iron, containing 4 lugs, each acting as a magnet motor pole. For the activation of this core, the stator of a commercial 12-pole magnetic motor (coils) was used. These 12 coils were interconnected in order to compose 3 phases of 4 coils. The phases of the stator are energized sequentially, based on signals generated by reflective type photo detectors that detect the passage of stamped references on the side face of the flywheel.
Upon detecting a reference, the photo detector transmits a low voltage signal to the power board which sends it properly amplified to the corresponding phase of the motor, synchronized with the angular position of the rotor.
The rotor: The prototype rotor consists of the axle, flywheel and core (rotor) of the engine. The motor core and the two neodymium magnets were coupled to the shaft by means of interference fit. At particularly high speeds, as required in the DCMS, a number of considerations are required so that the inertia wheel (flywheel) does not disintegrate due to high centrifugal forces. The studies in this respect will be presented in later work. As already mentioned in this work, it will not be considered a particularly high rotation and therefore a simple wheel in polymeric material is employed.

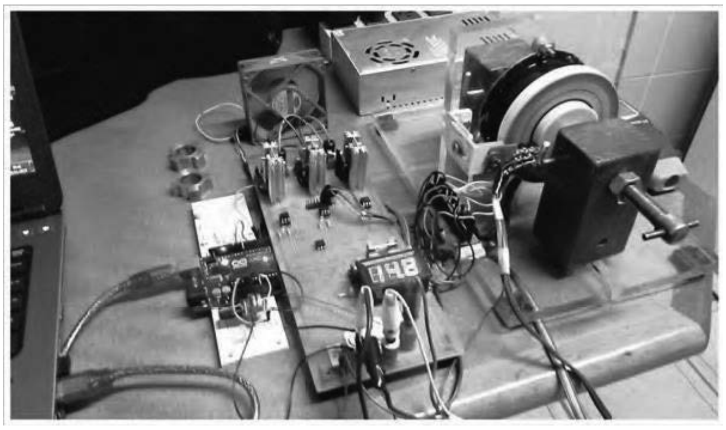

Fig. 3 shows the test bench with the assembled prototype assembly.

By adjusting this clearance to a minimum value and other adjustments, it was possible to achieve higher speed. This experimental result was in agreement with the statement made in Pavani (2014): "The smaller this resultant force, the less friction and the wear of the surfaces in contact". The following are the main experiments directly related to the bearings.
Tests of new materials for the pivots: In order to investigate the performance of other materials for the pivots, 5 different polymers (Nylon, Polyacetal, Teflon, PVC and hard rubber) were tested. First the 5 pivots were tested for the maximum rotation reached. Afterwards they were submitted to the rotation of 2,000 rpm for two hours, all under the same conditions. The wear was evaluated with the aid of a profile projector. The results are set forth in Table 1.

Tab. 1 - Performance of the different polymers used as pivots

Polimer	Maximum rotation speed (rpm)	Wear (mm) 2000 rpm/120min
PVC	2.7	0.05
Nylon 6	2.95	0.03
Teflon	2.9	0.10
Rubber	2.6	0.05
Poliacetal	2.7	0.07

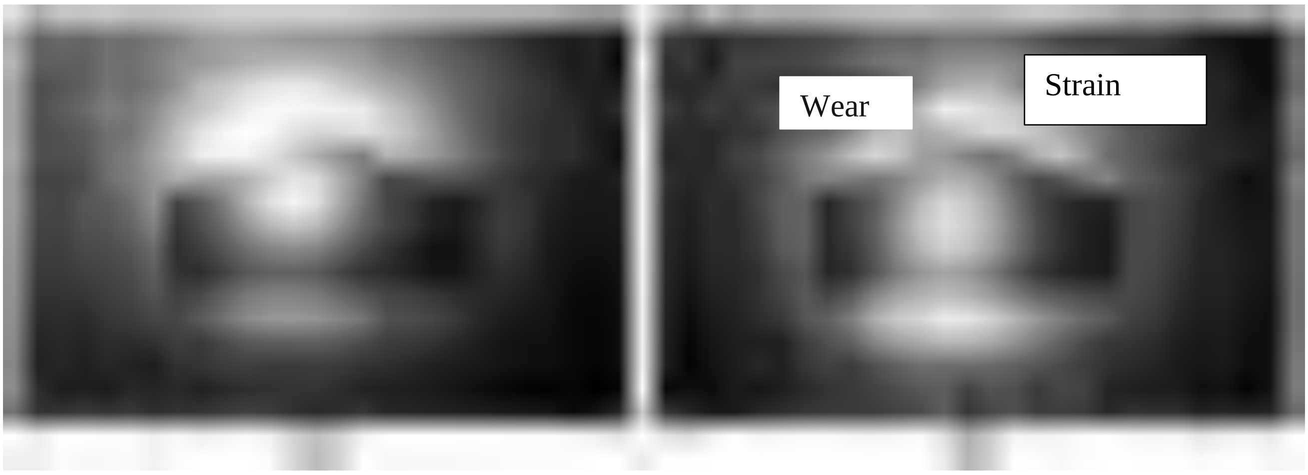

Fig. 4 images obtained on the profile projector. (A) Pivot before the test; (B) Pivot after the test.

Minimum rotor / stator air gap: Aiming to discover the smallest possible air gap, some experiments were performed with motor cores of different diameters. The minimum air gap that still allowed rotation without physical contact of the rotor with the stator was 0.75 mm.

CONCLUSIONS

This work is part of a study that aims to obtain guidelines for the DCMS project. In this larger study, challenges were discussed regarding the protection structure, the bearings, the rotor design, the drive and aspects involving the rotor dynamics. The present work focused on the bearings.

Considering the advantageous features such as extreme simplicity, compact size, the absence of maintenance, very low friction and reliability, and perfect adaptation to DCMS, the hybrid magnetic bearing model presented in Pavani (2014) was adopted in this work.

A small scale physical prototype was built and the bearing performance was investigated experimentally. New materials were investigated for the pivots and the best result was obtained with nylon 6. A magnetic device has been successfully developed to precisely balance the pulling forces of the two bearings. These two solutions, together with the adjustment of a minimum clearance in the bearings, provided very low friction and wear. Graphite powder lubrication has improved performance. Although limited, the radial stiffness of this magnetic bearing proved sufficient to maintain rotor stability.

This bearing model was very promising for DCMS. Even using a relatively simple and relatively small prototype, rotations near 12,000 rpm were achieved.

Certainly much higher rotation speed can be achieved with a larger prototype, made with more rigid and precise elements and more advanced materials, being driven by a more powerful engine controlled by a more advanced digital / electronic system. Obtaining speeds closer to those required for the DCMS (96,000 rpm) requires more studies not only on the bearings but on the whole DCMS assembly. Attaining greater rotation speed the studies carried out in the larger work become more relevant: design of the rotor to resist centrifugal forces, rotor dynamics, structure design and others.

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