TOWARDS A NEW BALL BEARING CAGE TO ADDRESS CAGE INSTABILITY

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ABSTRACT

The role of a ball bearing cage is to separate the balls and to equivalently distribute them around the whole bearing. However, under certain circumstances, the cage exhibits dynamical instabilities. Indeed, repetitive impacts of the cage with the rolling elements or the rings may lead to an erratic behavior. Those persistent rebonds within the bearing induce a significant increase in the bearing power losses and also in the frictional bearing torque. In the worst-case scenario this could even result in a ball bearing seizure. Space applications have been particularly concerned by cage instabilities for the last decades.

The paper proposes a new cage dynamics model in order to understand the nature of cage instabilities and then to counteract them. The description of this deleterious phenomenon is performed by providing an insight of an experimental test campaign, which was specifically dedicated to the study of the cage motion. The goal of the tests was to validate the cage model as well as the understanding of the physical mechanisms that govern cage instability. Several bearing and cage configurations were investigated. As a result, the key internal parameters were identified and directly linked to the starts of cage instability phases for the tested bearings.

1. INTRODUCTION

Space applications naturally induce harsh working conditions for ball bearings. Maintaining a satisfying working behavior of such components during whole space missions is a continuous challenge. Indeed, it is quite common for ball bearings to endure high speed, high loads and harsh conditions that are not suitable for mechanical devices. We think for example of bearings that work in vacuum, such as those equipping reaction wheels and gyroscopes. Without surprise, those conditions met in space are favorable for the appearance of some harmful phenomena related to ball bearings.

Among them, one may find occurrences of an unstable movement of the ball bearing cage. The so-called cage instability is characterized by an erratic motion of the separator between both rings and the balls. This leads to a sudden, intermittent and big increase in the bearing torque. This situation can get worse. Indeed, if the kinetic energy of the cage becomes too high, then the cage may fail due to the intensity of the loads. Cage instability is a real concern for all advanced space applications that use roller or ball bearings.

Reported ball bearing failures are numerous regarding space probes and satellites. Among them, one may point out a significant amount of ball bearing failures that are due to cage instability. For example, reaction wheels of recent space missions have been affected : Rosetta (ESA) [1], Newton-XMM (ESA) [2] or Cassini (NASA) [3]. The loss of one or several reaction wheels leads, at least, to a modification of the initial sequence of the mission. In such a situation, a skilled team must analyze how to maintain a correct behavior of the spacecraft on a case-by-case basis [4]. In addition to a loss of time and money, it is common to see the initial mission reoriented or even shortened. Of course, the worst situation would be the complete loss of the space probe or the satellite. And bad events are numerous…

The paper introduces a new computational tool that aims at modeling the dynamics of ball bearing cage. The fundamental purpose of this model is to provide a clear picture of the influence of the key parameters that govern cage instabilities. Among other things, this new tool should give to the space mechanism designers the capability to improve the reliability of their assemblies, by notably preventing occurrences of cage instability.

A large part of the paper is dedicated to the experimental validation of the cage model. From one side, this is done in order to give an insight of the different steps that were realized during the test campaign. On the other hand, this way of doing would also facilitate the introduction of the essential elements that constitute cage instability, which are *a priori* difficult to discern.

Finally, the possibilities provided by the computational model are briefly mentioned. They notably concern the development of a new unconditionally stable cage. The latter was entirely designed by starting from the deep understanding of the specific physical aspects behind the cage instability phenomenon.

2. CHARACTERIZATION OF CAGE INSTABILITY

2.1. Cage instability

Currently, research is still ongoing because of a lack of definitive solution. The main obstacle comes from the nature of the cage instability phenomenon, which is still not clearly defined. In other words, the hidden mechanisms that drive cage instabilities have not been identified. For instance, some studies define cage instability through purely quantitative criteria [5, 6, 7]. Some other works attempt to understand cage instability only *via* consequences that are induced by cage instabilities (noise, cage seizure, overheating, increase in bearing torque,…) [8]. Also, other researchers propose some qualitative approaches to characterize cage instability, such as: "when motion increases, the cage becomes unstable" [9], "disturbances in the cage motions" [10] or "chaotic vibration of the cage" [11]… But, from a more general point of view, nothing has been proposed yet to definitely counteract this dangerous dynamic phenomenon.

The common point of all the attempts used to describe cage instability is a sudden and unexpected rise in the kinetic energy of the cage. As a matter of fact, if the mean kinetic energy of the cage increases, then the intensity of all the impacts occurring with balls and rings would also increase. This would obviously lead to bearing torque spikes and to a new source of noise inside the bearing itself. Conversely, if there is no increase in the kinetic energy of the cage, then the separator would not cause any trouble regarding the bearing torque and would thus not significantly affect the bearing behavior.

A deep understanding of the root causes of these rises in the kinetic energy of the cage must ultimately allow engineers to improve their design, which prevents instability to occur. To that purpose, it appears necessary to have a cage model specifically dedicated to cage instability at one's disposal.

2.2. New model of the cage dynamics

Despite the complexity of the physical phenomena that govern the cage dynamics, the new modeling tool was developed in order to be both robust and reliable. Hence, an innovative integration method was specifically adapted to solve the set of non linear equations that are part of the foundations of the model. In the present case, the problem is solved by using an implicit integration scheme, which allows an absolute control regarding the error performed on the Newtonian equilibrium.

For simplicity purposes, the modeling of the cage dynamics is explicitly focused on the planar motion of the cage. Indeed, it is worth mentioning that cage instabilities take place in the particular plane that is perpendicular to the bearing axis [12]. As a result, such simplification appears to be relevant regarding the initial goal of the numerical tool.

This new model of the cage dynamics necessitates to have *a priori* a precise knowledge of the ball bearing equilibrium, which is thus considered without its cage. In other words, the cage model uses the classic outputs provided by a ball bearing software before starting any simulation. This includes, for example: the ball/race contact forces, the kinematical variables of the balls, the contact angles under loading, etc. Typically, such data can be provided by computational codes based on a quasi-static formalism. Notably, this approach is the one used by the ball bearing software CABARET, which is edited by ESTL [13]. Besides, at the time of drafting this article, the integration of the new cage model in CABARET is ongoing.

3. EXPERIMENTAL VALIDATION

An experimental test session was carried on at ESTL's facilities. The first purpose was to study the occurrences of cage instability on a specific ball bearing by observing the influence of several parameters. In a second time, test results were used to establish the validation of the numerical model of the cage.

3.1. Experimental tests

3.1.1. Test rig

The test rig that was used for the study of the cage behavior is comprehensively described in [14]. To sum up, two kinds of measurements were available:

1. *A direct motion capture of the cage.* The test rig configuration is such that the top face of the tested bearing is visible and located at the top of the rig. Hence, it allows the use of a high speed camera (4000 frames per second, 1024 x 1024 pixels) in order to record the motion of the cage in the plane that is perpendicular to the bearing axis (Fig. 1). For each of the tests, the trajectory of the cage's center was rebuild by analyzing each picture separately. This was achieved by identifying the edges of the different objects (*viz*. the cage, the rings and the balls) present on each of the pictures, as depicted in Fig. 2. Such a procedure was performed by using the image processing toolbox of MATLAB. This process was not easy to put in place, mainly because of the small cage/race clearances, as well as the limited resolution of the high speed camera. This required a laborious filtering process in order to exploit the results. Nevertheless, despite the sensitivity to cage/race clearances, the process led to successful results, as it will be described in Sec. 3.2.1.
2. *Both low and high frequency torque measurements.* The test rig is equipped with Kistler sensors. These sensors are disposed in such way that the torque of the tested bearing is directly available. Torque data are available at two sampling rates: 10 Hz and 2000 Hz. The low rate acquisition allowed us to identify sudden steps in the torque, which are representative of cage instability occurrences. On the other hand, the high rate acquisition torque displayed the cage instability signature in the spectrogram of the torque, as it would be shown in Sec. 3.2.2.

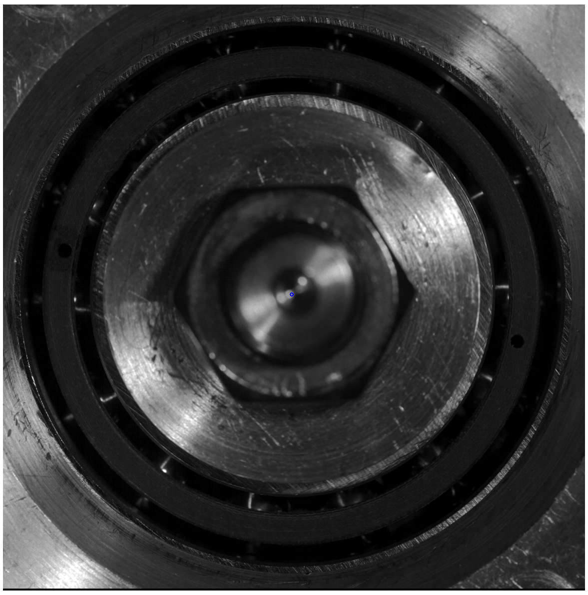

Figure 1. Example of bearing picture recorded by the high speed camera

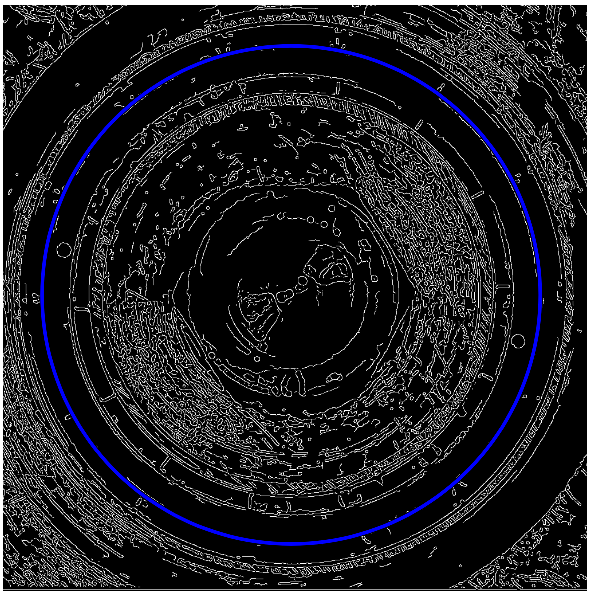

Figure 2. Example of bearing picture processed by MATLAB

3.1.2. Tested bearings

Ball bearing that were tested were all *SKF7005 CD/ P4A*. Their characteristics are provided in Tab. 1.

3.1.3. Test conditions

Ball bearings were tested in the following conditions:

- A soft axial preload of 150 N was applied to each of the tested bearings. This was performed by using Belleville springs.
- The rotating speed of the tested bearings was between 0 rpm and 2000 rpm. The detailed profile of the tests is provided in Fig. 3. The purpose was to reach two speed plateaux of 2000 rpm in both clockwise and counterclockwise directions.
- All the tests were performed at ambient temperature. Considering the short duration of the tests (around 160 seconds), no temperature measurements were performed.

Bearing outer diameter	47 mm
Shaft diameter	25 mm
Inner diameter of the outer ring	39,9 mm
Outer diameter of the inner ring	32,1 mm
Pitch diameter	36 mm
Ball diameter	6,35 mm
Conformity	0,51 - 0,52
Ball complement	14
Contact angle	15º
Cage material	Tufnol Grade RLF/1 (cotton reinforced phenolic resin)

Table 1. Details of the bearing *SKF7005 CD/ P4A*

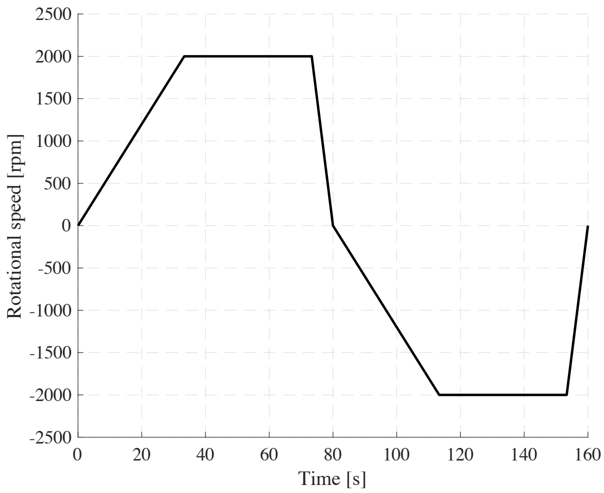

Figure 3. Speed profile of the tests

3.1.4. Test parameters

Essentially, three parameters were selected in view to investigate their influence on cage instability:

1. A first cage was successively machined in order to vary cage/outer race clearance from 0,2 mm to 0,9 mm, from test to test. A second cage was also used with a big clearance of 1 mm. The cages were all guided by the outer race.
2. A removable metallic pin was added on the cage during several tests. This allowed to create a cage imbalance. The mass of the cage was between 1,512 g and 1,782 g, following the cage/outer race clearance. The mass of the pin was about 0,074 g.
3. The lubrication conditions were modified between the different tests in order to change the friction level. Most of the tests were carried out in dry conditions. Otherwise, some lubricant (Fomblin Z25 oil) was added. Three different amounts of oil were selected during the lubricated tests: 4 µl, 40 µl and 80 µl.

The parameters and the nomenclature of the tests are provided in Tab. 2.

Configuration	Cage/race clearance [mm]	Lubricant	Cage imbalance?
1	0,2	Dry	No
2	0,2	Dry	Yes
3	0,4	Dry	No
4	0,4	Dry	Yes
5	0,9	Dry	No
6	0,9	Dry	Yes
7	1	Dry	No
8	1	Dry	Yes
9	1	4 µl Z25	No
10	1	40 µl Z25	No
11	1	80 µl Z25	No
12	1	80 µl Z25	Yes

Table 2. Test matrix

3.2. Results and correlation

3.2.1. Motion of the center of the cage

The instability of the cage can be directly linked to the whirl, which is a very rapid translational motion of the cage's center around the bearing axis. Indeed, an increase in the whirl corresponds to an increase in the kinetic energy of the cage. This specific motion was clearly identified on the pictures recorded by the high speed camera and by applying the filtering process described in Sec. 3.1.1.

A typical example is given in Fig. 4. It is related to the experimental test of the configuration nº7 (Tab. 2), during the speed plateau of the clockwise phase (Fig. 3). It corresponds to approximately one complete revolution of the group of balls around the bearing axis. It has to be emphasized that the whirl of the cage is not centered on the bearing axis. Indeed, it seems that the cage "whirl center" rotates around the bearing axis to finally exhibit a "rosette-like" pattern. This means that the trajectory of cage's center is close to a circle, which itself turns around the bearing axis. As a result, by considering the number of superimposed circles that can be guessed in Fig. 4, the whirling behavior of the cage is far more rapid than the rotation of the balls around the bearing axis. The frequency of the whirl was located between 800 Hz and 850 Hz during the speed plateaux (Fig. 3). By noting that the bearing motion was 33,333 Hz (2000 rpm), the motion of the group of balls was estimated at 13,864 Hz. Thus the whirling motion of the cage is approximately 60 times bigger than the rate of the group of balls.

The phenomenon was reproduced by the model of the cage dynamics. The result is depicted in Fig. 4, which also corresponds to the configuration nº7, in the same speed conditions (2000 rpm). As shown, the whirl appears to have the same features, with the same "rosette-like" shape.

From a general point of view, the whirl was expected in both numerical and computational results. But the "rosette-like" pattern was a surprise at first sight. Nevertheless, the model was able to highlight the root causes of the phenomenon. This occurred mainly because the balls were never perfectly evenly distributed within the bearing. Indeed, a symmetrical position of the balls would have implied a whirl centered on the bearing axis. By allowing a random position of the balls, the numerical model demonstrated that the cage whirling motion followed the geometrical center of the ball group. This center moves on a circle centered on the bearing axis. Thus the combination of the whirl of the cage and the balls give the "rosette-like" shape observed on the test rig.

A stable motion of the cage exhibits a totally different behavior. Fig. 6 depicts the particular case of the experimental test of the configuration nº5 (Tab. 2), for three revolutions of the group of balls that occurred during the speed plateau of the clockwise phase (Fig. 3).

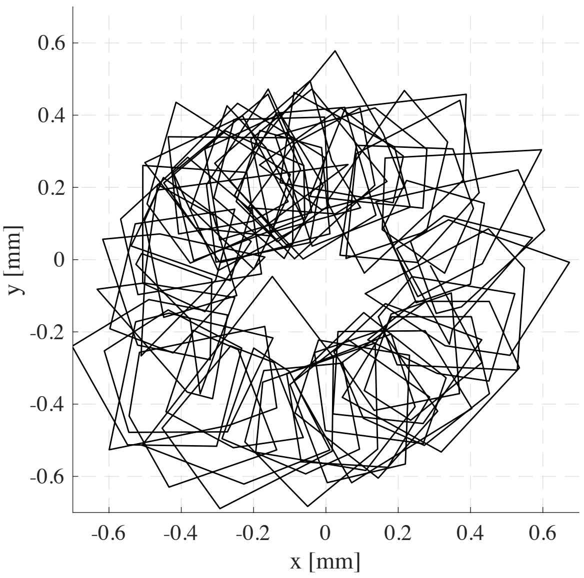

Figure 4. Motion of the geometrical center of the configuration nº7 (experimental)

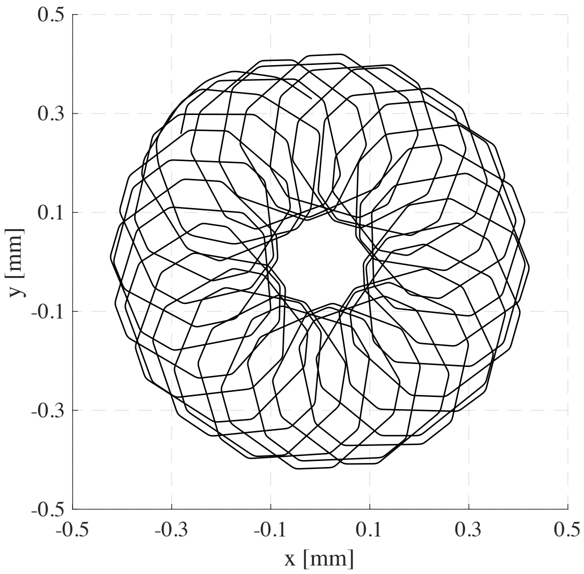

Figure 5. Motion of the geometrical center of the configuration nº7 (numerical)

As it can be observed, there is no evidence of whirling motion. On the contrary, the trajectory is made of three superimposed circles that are centered on the bearing axis. This implies that the cage geometrical center follows the group of balls at the same rate.

The stable behavior of this specific experimental test was also numerically reproduced by the cage model. Fig. 7 depicts the result obtained for the configuration nº5. The conclusions are identical to the ones performed for the experimental tests.

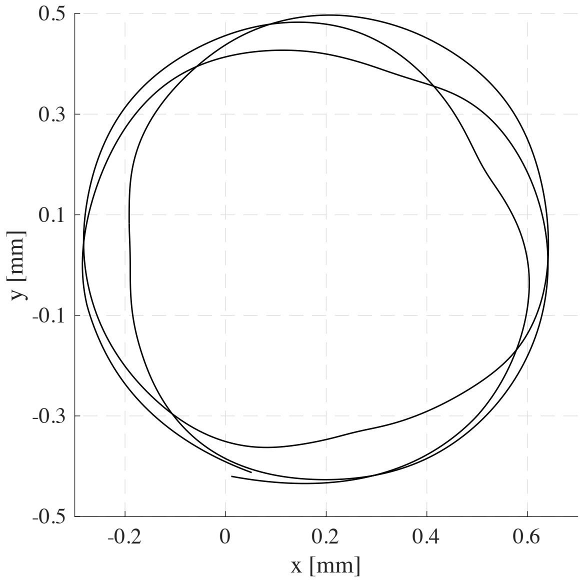

Figure 6. Motion of the geometrical center of the configuration nº5 (experimental)

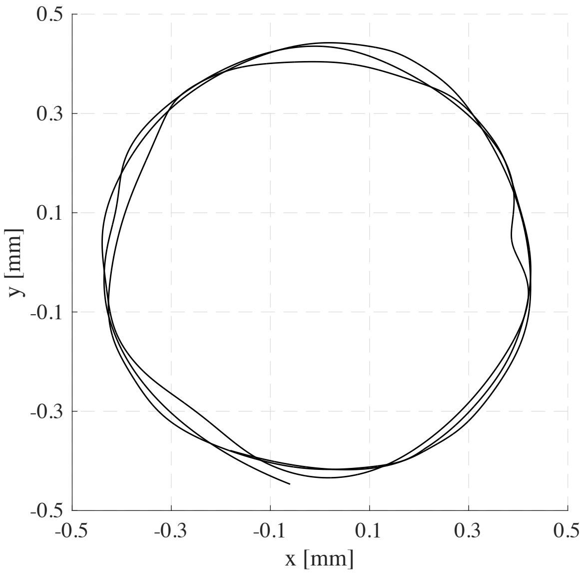

Figure 7. Motion of the geometrical center of the configuration nº5 (numerical)

3.2.2. Ball bearing torque

Data from the experimental tests showed that cage instabilities significantly increase the mean value of the torque of the ball bearing. As an example, Tab. 3 lists the averages of the torques measured on the test rig for the configuration nº5 (Tab. 1) of the bearing. This specific configuration was tested three times, by following the test profile of Fig. 3. The case nº5 is of particular interest, because it exhibited an alternation of stable and unstable phases. It was observed that the bearing torque was multiplied by 3 to 7, just by switching from a stable to an unstable phase of the cage.

Such big jumps were also computed by the numerical model of the cage dynamics. Fig. 8 depicts an example of unstable torque, which was computed by using the parameters of configuration n°5. The black curve corresponds to the raw results provided by the model. The numerous peaks are representative of the ball/cage impacts during the functioning of the bearing. The red curve is a moving average of the computed torque. As expected, the rise in the torque has the same order of magnitude as the increase in the torque measured on the test rig during unstable phases.

Test	Clockwise phase		Counterclockwise phase	
	Mean Torque [N.mm]	Stability	Mean Torque [N.mm]	Stability
1	14,6	Unstable	4,2	Stable
2	3,8	Stable	2,1	Stable
3	11,2	Unstable	11,9	Unstable

Table 3. Measured torque for the configuration n°5

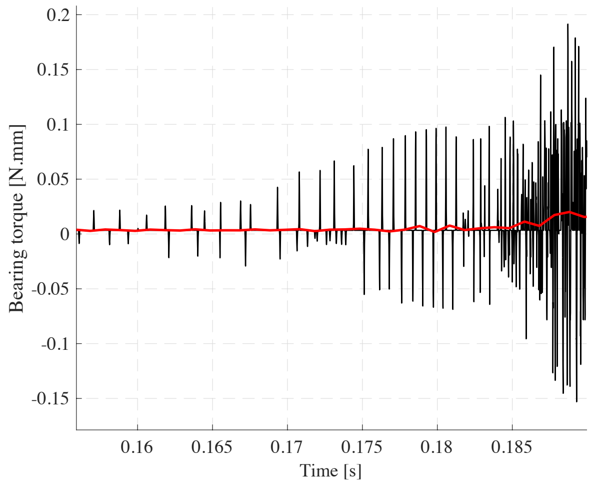

Figure 8. Computed torque for configuration n°5 during an unstable phase

Fourier transforms of the torque were also performed by using the data from the high frequency measurements (sampling frequency of 2000 Hz). Fig. 9 gives a comparison between torque spectra of both stable and unstable cases.

By considering the torque spectrum of the stable case in Fig. 9, several peaks between 250 Hz and 300 Hz can be observed. They corresponds to the impacts between the cage and the balls. Indeed, this statement was confirmed by the numerical tool, which estimated that the frequency of these impacts is close to the one measured on the test rig.

The signature of cage instability is clearly visible in the spectrogram of an unstable cage. Indeed, the spectrogram of the bearing torque shows a distinct peak slightly above 800 Hz, which corresponds to the whirl motion estimated with the high speed camera. Also, a concentration of peaks is present at a frequency significantly lower than the whirl of the cage, around 300 Hz. This is due to the limited sampling frequency, which led to aliasing.

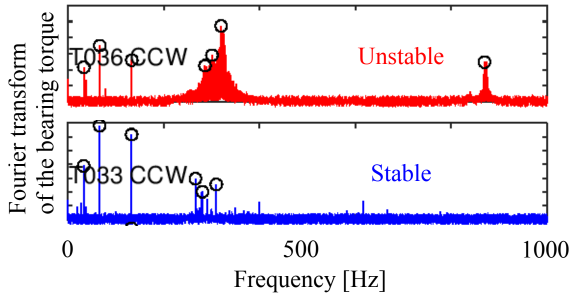

Figure 9. Fourier transform of the bearing torque of stable (configuration n°5) and unstable (configuration n°7) experimental tests

3.2.3. Influence of test parameters

Tab. 4 synthesizes both experimental and numerical results regarding cage instability. As exposed in the previous sections, stable and unstable phases of the cage that were observed on the test rig were also successfully reproduced by using the computational model of the cage dynamics. This statement concerns both the motion of the geometrical center of the cage and the torque of the bearing. These findings are valid for all the parameters listed in Tab. 2.

As expected, the lubricant has a beneficial effect on cage instability. Without surprise, this is due to the global decrease in the friction.

At the opposite, the mass bias of the cage does not seem to produce any change regarding cage instability. Even if the trend appears to be strong, the generalization of this conclusion cannot be definitely demonstrated.

In the present case, a trend seems to emerge concerning the influence of the geometry of the cage on its dynamic behavior. As a matter of fact, a transition between stable and unstable phases occurs around a cage/ring clearance of 0,9 mm. Nevertheless, it has to be emphasized that this apparent relationship between the cage diametral clearance and instabilities cannot be generalized. For instance, other working conditions (rotating speed, bearing loads,…) or other kinds of cage material could have completely changed this link between the design and the behavior of the cage. As a consequence, care must be taken and cage instability should be investigated on a case-by-case basis.

Test	Stability	Test/model correlation?
1	Stable	Yes
2	Stable	Yes
3	Stable	Yes
4	Stable	Yes
5	Stable/Unstable	Yes
6	Stable	Yes
7	Unstable	Yes
8	Unstable	Yes
9	Stable	Yes
10	Stable	Yes
11	Stable	Yes
12	Stable	Yes

Table 4. Results and correlation

4. CONCLUSION ET PERSPECTIVES

The paper introduced a new computational tool, which aims at providing a better understanding of the cage instability phenomenon. The paper also highlighted some of the fundamental aspects regarding the nature of cage instability. This was done notably through the description of a test campaign dedicated to the study of cage dynamics. Moreover, occurrences of cage instability were linked to some variations in the relevant parameters that govern the problematic phenomenon. Among other things, an insight into the influence that cage geometry, mass bias and friction could have on the cage dynamics was proposed. The correlations that were observed between experimental and computational results naturally led to the validation of the new model of the dynamics of the cage.

The results presented in the paper allow a connection between the new model of the cage dynamics and the ball bearing software CABARET, in collaboration with ESTL. In the end, the purpose is to contribute to enhance the capabilities of CABARET, especially regarding the influence of the cage on the bearing behavior. In this way, the authors think that this add-on concerning the cage will help the European space community by providing an efficient tool to protect space mechanisms from cage instabilities.

Also, an intensive use of the cage dynamics model after the experimental test campaign led to a better understanding of the cage instability issue. Based on that, a new cage design was elaborated in order to exhibit an unconditionally stable behavior, no matter the conditions encountered by the bearings (load, speed, temperature, lubrication, etc.). This particular cage was also recently tested, both mathematically and experimentally. Hence, the main purpose of these tests was to prove that even unfavorable working conditions could not force instability. For instance, several metallic prototypes were manufactured and experimentally tested without any lubricant in order to impose very high friction. Despite such extreme conditions, which were significantly favorable to cage instability occurrences, these tests were successful and demonstrated the robustness of the new cage concept. A patent application has been filled and the patenting process is currently ongoing.

The new cage is ready for industrialization. The next step would be to identify the best way to integrate this unconditionally stable cage in critical space mechanisms that require very smooth and reliable behavior, such as reaction wheels. Turbo pumps of launcher could also get benefit from this new technology. Lastly, even if cage instability has been clearly identified is space applications, the odds are high that other fields experience troubles linked to cage instability, with or without being aware of it. We think for instance to electrical motors or spindles of machine tools. An exploratory work has been started to identify if cage instability affects those fields as it affects space applications.

5. ACKNOWLEDGMENTS

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