# APO-GEE TALK

## Innovative thinking for ball bearing engineering

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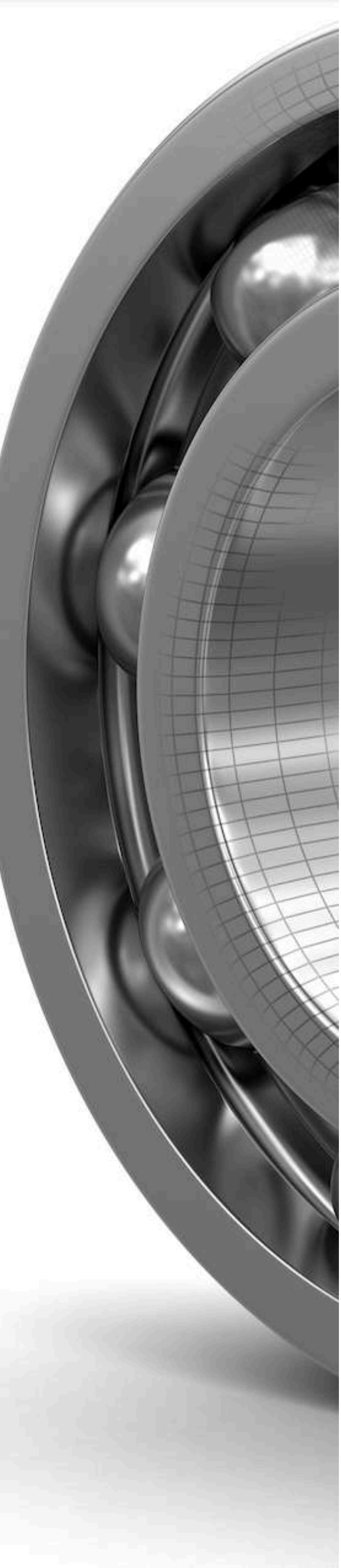
APO-GEE
BALL BEARING ENGINEERING

Volume #3
February 2024



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# Editorial

Dear Readers,

As we proudly unveil the third edition of our magazine, we are thrilled to continue our journey of exploration and discovery in the realm of ball bearing engineering and innovative product development.

Within the "Bearing Physics" section, we delve into the intricate world of gyroscopic torques and their significant influence. Understanding this impact is paramount in achieving excellence in ball bearing engineering.

Our "Innovation" segment introduces a groundbreaking method aimed at assessing bearing cage stability. This original approach epitomizes our commitment to pushing boundaries and creating reliable, high-performance solutions.

The "Engineering" section delves into practical cases, offering a detailed analysis of improving spindle performance in machine-tools. Additionally, we explore how (no-)gravity impacts bearing cage stability in RWA and gyroscopes, unveiling essential insights for future advancements.

This issue features also a discussion on the methodology associated with modeling bearing behavior, and the limitations of purely calculative or AI-based approaches.

Lastly, this edition showcases an interview with Julien Demonty, the CTO of a groundbreaking player in the New Space arena, focusing on GMC innovations. Prepare for an enriching read with visionary insights.

We are honored by the positive comments received for our previous issue of APO-GEE TALK. Your feedback is invaluable, and we eagerly await further contributions from you!

Warm Regards,

Sincerely,

Sébastien Assouad
CEO APO-GEE

BEARING PHYSICS

# Toupie or not toupie?[1]

For many, the high rotational speeds of a ball bearing are almost exclusively associated with centrifugal force. And this is quite normal, as this very banal physical phenomenon is accessible to everyone, whether it has been observed or felt. Who has never seen the laundry in the washing machine nestling against the walls of the drum? Who has never had a heartbeat on a fairground ride? Who has never had the impression of feeling thrown out of a car approaching a corner a little too quickly? And, for the more discerning, who doesn't remember the adventures of the famous 007 Agent in a crazy centrifuge for astronauts? It is therefore imbued with a certain compassion that we

Fig. 1 – The effects of centrifugal forces

[1] Toupie is the French word for spinning top

think of these balls desperately pressed against the outer ring of the bearing, when the latter is launched at very high speed.

However, focusing attention on centrifugal force alone is too simplistic. Because, unlike James Bond, in addition to being wrung out, the balls turn on themselves. And that changes a lot of things.

To realize this, we must move, in a singular way, from Roger Moore to the spinning top; the behavior of the balls is also similar to that of the little toy from our childhood. Compared to the examples linked to centrifugal force, the parallel here is a little less obvious. Though...

A spinning top is a body of revolution that rotates around its axis of symmetry at a speed $\omega_{Spin}$ and subjected to its own weight $F_{Gravity}$ (Fig. 2), this force being applied to the center of mass of the toy. This involves a reaction at the base of the object in contact with a rigid surface. Gravity and contact reaction lead to the birth of a mo-

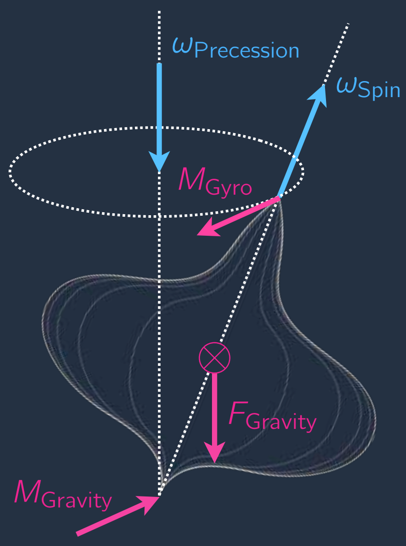



Fig. 2 – Spinning top dynamics

ment of forces $M_{Gravity}$, which tends to tip the spinning top. However, against all expectations, if it has sufficient rotation frequency, the spinning top does not fall. Instead, its spin rate $\omega_{Spin}$ rotates itself around the vertical axis and maintains its so-called precession movement $\omega_{Precession}$. This is only a translation of the principle of conservation of angular momentum: in reaction to

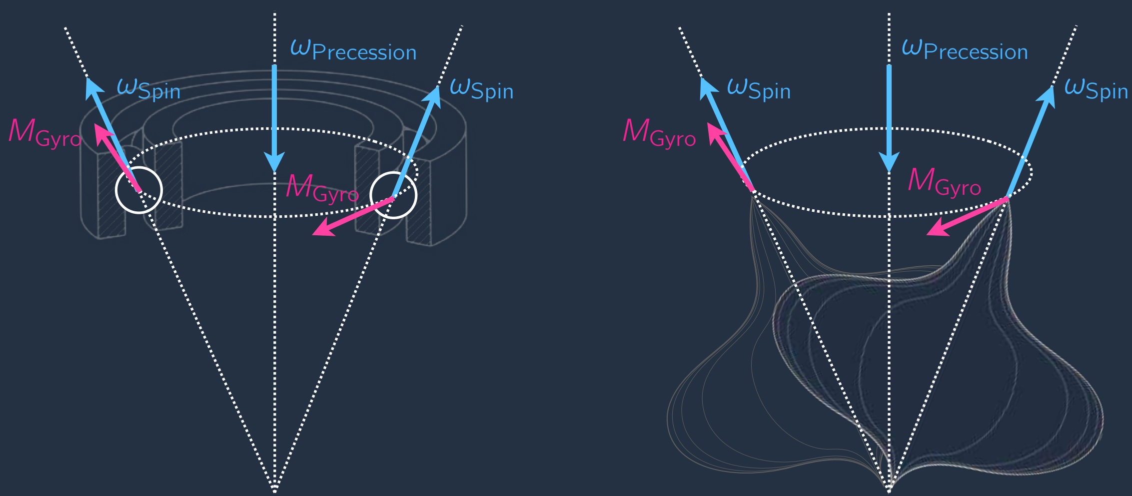



Fig. 3 – Parallel between the dynamics of the ball bearing and the spinning top

the moment which acts on it, the spinning top opposes a gyroscopique torque $M_{Gyro}$.
Let us return to our balls, to our spherical spinning tops, and take a simple case: that of a bearing loaded axially. The balls are now all in the same state, regardless of their respective position around the circumference of the bearing (Fig. 3). They rotate on themselves in a certain direction, materialized by the vector . However, as these balls also rotate around the axis of the bearing, this means that the direction of the balls' spin is constantly modified: this vector rotates around the axis of the bearing at the same rate as the balls. In other words: the balls have a precession movement, similar to that of the spinning top.
To understand it better, let us consider the opposite thought pattern to that used to study the spinning top. Basically, by imposing a trajectory around the axis of the bearing, we force the balls to change their rotation. This amounts to dictating an untimely reorientation of the axis of rotation of all the spinning tops which equip the bearing. However, Newton's laws are implacable: this movement imposed on the balls implies a reaction. This is a gyroscopique torque .

The gyroscopic torque of a rolling ball is applied mainly in the direction of peripheral advance of the balls. In other words, it tends to force a spin component of the ball in a direction perpendicular to the rolling movement on the rings. This is similar to the kinematics of a seasoned player's bowling ball: the rotation given to the ball tends to bring it back towards the center of the lane while it progresses towards the pins.

Although less accessible to the senses, the gyroscopic torques applied to the balls greatly influence the behavior of high-speed bearings. And their impact is multiple. First of all, as do centrifugal forces, gyroscopic torques significantly modify the internal forces of the bearing, as well as the contact angles and pressures. Also, depending on their intensity and for lightly loaded bearings, these torques can be responsible for a skidding phenomenon, that is to say an overall sliding instead of a rolling movement of the balls. Such a situation leads to significant overheating or even destruction of the mechanical organ.

To spin and let roll!

Christophe Servais
CTO APO-GEE

# How (no-)gravity impacts cage instability in RWA and gyros bearings

Fig. 1 – Space probe qualification challenge

**Cage instability in bearings**

The cage instability phenomenon in gyroscopes' and RWA's ball bearings is not without consequence. It generates noise and vibrations that significantly affect the normal operation of the equipment. Over the last few decades, numerous space missions like Rosetta, GOES, Cassini, XMM-Newton, and many others encountered substantial disruptions, with some even being aborted due to ball bearing performance issues.

The common denominator among these mission setbacks is the cage instability problem in bearings. This problem resembles the chaos theory's butterfly effect—it's a complex and chaotic issue that has been hard to predict and widely misunderstood. This unpredictability has plagued space missions for years, causing uncertainty and costly setbacks.

**Can we rely on qualification?**

A natural question arises: can a successful qualification of the gyroscope or RWA guarantee cage stability once the spacecraft or satellite is launched into space?

The answer is definitively negative, and for two essential reasons.
The first reason lies in the intrinsically chaotic nature of the cage instability phenomenon. This means that slight modifications in operational conditions (speed, friction, etc.) or slight changes in the cage's geometry can trigger cage instability. Many parameters indeed contribute to triggering this phenomenon. No matter how extensive the qualification, it's nearly impossible to precisely predict the actual evolution of operational conditions or wear, for example. The nature of the phenomenon also means that studying and testing extreme or limit cases cannot guarantee proper future functioning.

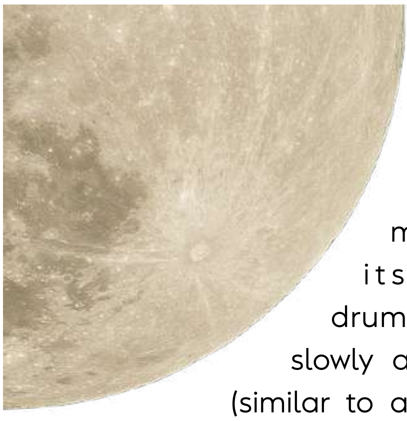
The second reason is directly linked to the first. It's related to the fact that experimental tests and qualification of bearings generally consider the presence of gravitational force. But what is the impact of gravity on the bearing cage's stability? Experimental tests cannot disregard gravity for an obvious reason, and numerical simulations account for it for realism, aiming to replicate the experience. But what about the ABSENCE of gravity? Experimental tests won't be of any help since gravity cannot be removed by any means.

Fig. 2 – Laundry behavior
in washing machine analogy

**The weight of the cage negligible, really?**

However, the weight of the cage is negligible, around some millinewtons. How then could such a weak force play a significant role on a spacecraft's scale? Cage instabilities merely translate the establishment of a coherent mechanism that tends to amplify exponentially. In other words, regardless of the intensity of the efforts identified once instability sets in, it always starts from an extremely calm situation. Thus, even an infinitesimal force, like the cage's weight, can undoubtedly influence the cage's movement. This is particularly true at low speeds or in transient regimes, where the cage's kinetic energy cannot produce inertia forces much greater than those generated by gravity. Consequently, the mechanisms involved in the birth of instability cannot operate; they are constrained by the cage's weight, which tends to maintain it in a stable state.

This reality changes as the bearing's rotational frequency increases. We can draw here the analogy of the washing machine. The cage undergoes its own weight just as



laundry in a washing machine undergoes its own. When the machine starts its cycle, the drum rotates very slowly around its axis (similar to a bearing ring). The clothes are slightly jostled but remain confined to the lower part of the drum: the weight of the damp laundry is enough to keep the mass within the machine's drum. However, as soon as the cycle reaches its spin speed, between 1000 and 2000 revolutions per minute, the laundry gets pressed against the walls of the drum. At these speeds, the centrifugal forces are much greater, and the weight fades in comparison, as if it ceases to exist. It's precisely this transition that the cage of the bearing experiences when its rotational frequency increases. In the same manner, with the increase in the cage's kinetic energy, gravitational force gradually fades in the face of inertia effects, eventually becoming negligible. It's only at this moment that the unstable nature can be observed, if it exists. The tragic corollary is that terrestrial experimental tests cannot anticipate a potential tendency toward instability at low and moderate speeds! In practice, the targeted speed ranges fall within the standard operation of the RWA or gyro incorporating the bearings. In such cases, predicting a FAILURE ON EARTH appears impossible! With the possible disastrous consequences that can be imagined.

**Mitigating risk is definitely possible**

Based on the deep understanding of the mechanisms driving cage instability, APO-GEE has engineered a new cage design, the Butterfly cage, that is intrinsically stable and has been experimentally validated (patent pending). APO-GEE also knows perfectly how to assess the instability risk associated with any cage, beyond terrestrial qualification, while also considering the effect of non-gravity.

For additional information and concrete demonstration based on real applications cases, contact us via www.apo-gee.tech.

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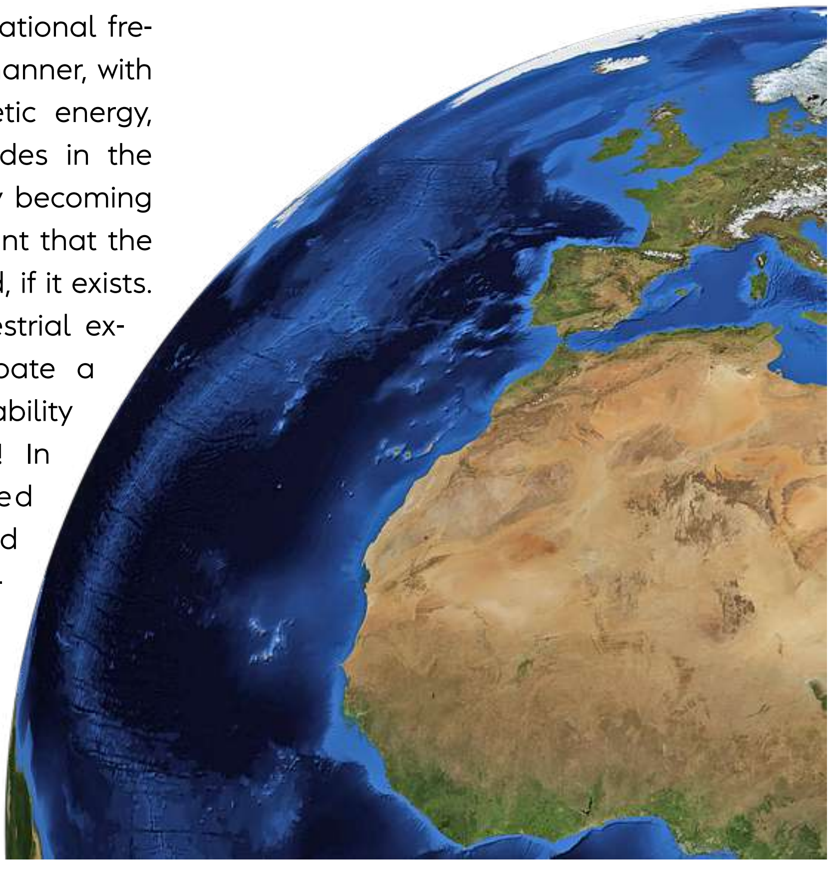


# Drastically improving ball bearing behavior

# The case of machine-tool spindles

The performance and precision of machine-tool spindles are intimately linked to the performance of ball bearings. The requirements and expectations in terms of machining precision demand precise, smooth, and harmonious operation of the bearings, as well as a limitation of noise and vibrations. This is why particular attention has been given to the development of so-called high-precision bearings, especially with the introduction of ceramic balls and the continuous improvement in ring machining precision. Undoubtedly, these developments have contributed to enhancing performance.

But can we speak, in recent years, of a significant or drastic improvement in performance? Can we also assert that spindles no longer suffer from unknown or hardly predictable issues? Or in other words, is it still possible to envision very significant gains in terms of operation and precision, well beyond incremental improvement?

To answer this question, let's consider two problems well-known to specialists in the machine-tool spindle or ball bearing industry: the Ball Speed Variation (BSV) problem on one hand, and the rattling noise problem often observed on the other.

**Towards Optimized Management of BSV**

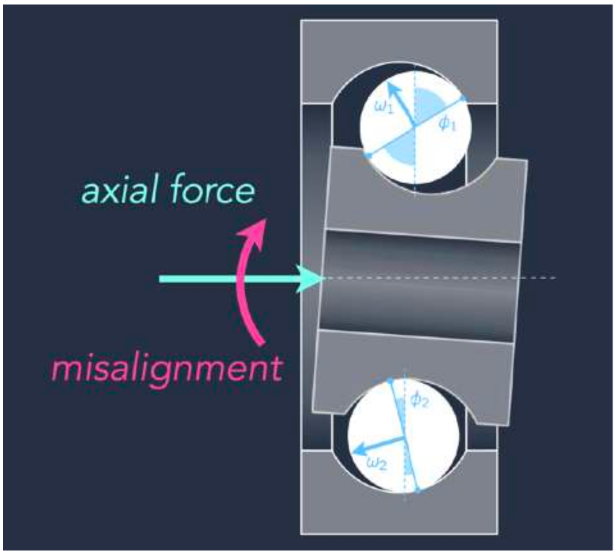



Fig. 1 – Effects of misalignment

Spindle bearings are generally subject to a combination of axial and radial loads. Those variously loaded bearings induce misalignment of the rings, leading to the Ball Speed Variation phenomenon, which manifests as non-constant ball advancement speed. This phenomenon can result in cage failure, noise, vibration, and excessive heat. Current available bearings only offer a partial solution to this problem. Deep groove and angular ball bearings can only tolerate a small amount of misalignment, roller bearings must also maintain perfect ring alignment, and while self-aligning bearings can tolerate more significant misalignment, they cannot support axial loads due to the outer ring geometry. In other words, combating BSV has always demanded a compromise from mechanical assembly designers.

After decades during which mechanism designers had to accept difficult compromises, APO-GEE now offers them a solution that opens up new perspectives: the Cobweb Bearing. The design of this new Cobweb bearing significantly reduces the adverse effects of misalignment. It can support a combination of axial and radial loads, just like deep groove and angular bearings, but with considerably extended tolerance for misalignment, even at the highest speeds.

As surprising as it may sound, yes, we have engineered the bearing that operates with the utmost precision ever. We have proven it, and concrete quantification of the gain is definitely possible.

**Eliminating the Unpredictable Rattling Noise**

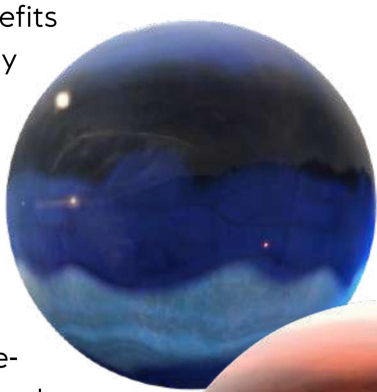
Most spindle manufacturers have been facing, for many years, an unexpected problem of random or entirely unforeseen noise and vibrations. This occurs sometimes even with new or relatively new bearings, with challenging consequences in terms of performance, customer perception, maintenance cost, and downtime. This issue comes with a frequency signature entirely different from the system's natural frequencies, nor classic bearing failing frequencies.

We have demonstrated, based on specific cases studied on spindle bearings, that the rattling noise problem is actually a bearing cage instability issue. Cage instability, well-documented in the field of space applications, is a phenomenon of a chaotic nature. This means that slight modifications in operational conditions (speed, friction, etc.) or slight changes in the cage's geometry can trigger cage instability. Many parameters contribute to triggering this phenomenon. The nature of the phenomenon also means that studying and testing extreme or limit cases cannot guarantee proper future functioning.

Numerous studies have been conducted over the years regarding the cage, particularly concerning material, to resolve the problem. Alongside this, and despite many attempts, it can also be stated that the design and geometry of the cage have ultimately evolved little. Thus, it is evident that we still haven't managed to eliminate the problem, nor even anticipate it. Worse, it can even be observed that the cage designs commonly used in high-speed bearings tend to promote cage instability! This is regrettable because high-precision bearings are high-value-added bearings (using ceramic balls, high precision in ring machi-

Fig. 2 – Rattling noise in spindles

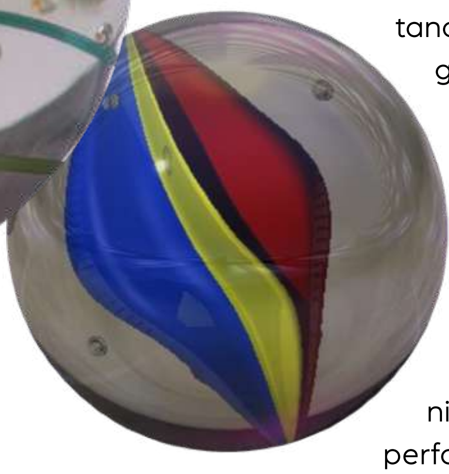
ning) whose benefits can be seriously compromised due to the cage instability problem.



For the first time, APO-GEE has developed a new inherently stable cage concept, the Butterfly Cage, which prevents any instability. Initially developed for space applications (reaction wheels, gyroscopes, turbo pumps), the cage integrates perfectly into machine-tool spindle bearings. Various analyses conducted on specific cases have demonstrated the value and performance of the Butterfly cage, not only in space applications but now also in machine-tool spindle bearings.

**New standards of performance**

While it may seem ambitious, even presumptuous, drastically improving the performance of bearings in machine-tool spindles is entirely possible. The Cobweb Bearing and the Butterfly cage are based on over 10 years of continuous and intense R&D effort, which has allowed for fully computing the kinematics of the balls and understanding the mechanisms governing cage instability.



This knowledge, coupled with the development of new tools, undoubtedly allows envisioning new standards of performance in the demanding and fascinating world of precision machining.

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# How to check cage stability? The innovative method of STABILITY MAPS

**Cage instability, a complex phenomenon**

Cage instability in bearings is a dynamic anomaly with possible disastrous consequences that can occur under certain conditions in space applications (launchers, probes, and satellites). The phenomenon can also occur in other types of industrial applications such as in the machine-tool spindles or turbo molecular pumps for example.

The peculiar nature of cage instability is by its tendency to arise unexpectedly. Cage instability is a chaotic phenomenon that is often erroneously attributed to resonance.


Fig. 1 – The sudden nature of cage instability

Counterintuitively, there is no need for the bearing's operating conditions to deteriorate, nor is it necessary to await possible advanced wear: cage instability occurs without warning, at any moment.

Given that the failure can be sudden, the need to converge towards a satisfactory bearing design is strengthened accordingly. But without a detailed understanding of the fundamental aspects underlying cage instabilities, the choice is not available; and empirical methods have prevailed. And this might work: a new cage is designed, is tested, fails, and the process is repeated; a new cage is designed, is tested, fails, and the process is repeated... until a configuration that finally satisfies is achieved. At least, that's what is believed...

Because a rapid resurgence is highly likely! For instance, even a minor deviation in geometry can easily lead back to square one and trigger cage instabilities, undoing the arduous work imposed by the multitude of necessary trials. Moreover, this solution isn't transferrable: if cage instability occurs in another bearing, the work must begin anew; starting from scratch becomes inevitable... In all cases, no guarantees can be provided.

**What to do? STABILITY MAPS as a first key step**

The stability maps make it possible to highlight the 3 types of behavior rage a ball bearing cage can exhibit: stable, jostled (agitated), or unstable.

It is crucial to understand that an unstable ball bearing cage can have severe consequences on the overall performance of the

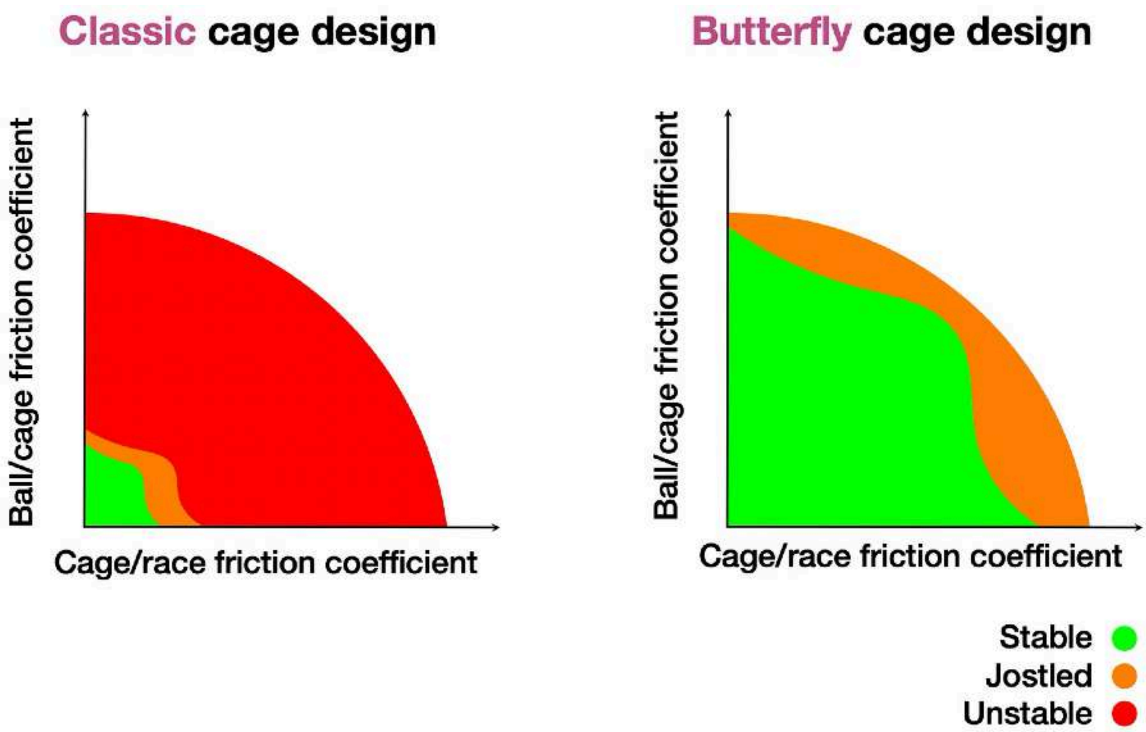


Fig. 2 – STABILITY MAPS

bearing, the mechanical system, or the assembly. The instability of the cage can indeed lead to unpredictable vibrations, increased friction, and premature failure of the bearing.

Therefore, thorough analysis and optimization of ball bearing cage stability are of utmost importance to ensure the reliability and longevity of the mechanical assemblies.

This is made possible by the implementation of an innovative technique based on the construction of original STABILITY MAPS, designed for addressing ball bearing cage instabilities. STABILITY MAPS aim to optimize the performance and reliability of ball bearing cages, and consequently, the bearings themselves, enabling engineers to design reliable mechanisms and assemblies. Based on the current geometry of the bearing and its operating conditions for one hand, and a deep and comprehensive knowledge of the mechanisms that govern the cage instability phenomenon for the other, it is now possible to accurately assess if and when a cage may become unstable.

The STABILITY MAPS will then tell whether for a bearing and a given application, the cage presents a risk of becoming unstable or not, and if so, within what limits. For example, STABILITY MAPS can reveal that a bearing will perform perfectly within a certain speed range. In other cases, the maps will show that the geometry of the bearing will be extremely sensitive to the phenomenon of cage instability and that the stability zone is particularly narrow. In this case, it will still be possible to ensure a perfect cage stability with the Butterfly Cage developed by APO-GEE (patent pending), a new cage design capable of countering any onset of unstable phase. Its performance has been demonstrated.

APO-GEE has established numerous STABILITY MAPS for concrete applications in different industrial sectors. They have undoubtedly made it possible to assess the risks on the bearings and then ensure their perfect functioning.

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INTERVIEW

# Julien Demonty

**CTO & Co-Founder**
VEOWARE
www.veoware.space

**What is your professional background and what are your responsibilities within VEOWARE?**

I'm a physician Engineer from background. I have experience in the aeronautic, chemical and space industry as aerodynamic and mechanical engineer and as project engineer. I have co-founded Veoware Space with Julien Tallineau in 2018 and I'm now responsible for the technical development at Veoware.

**What is VEOWARE story and what specific technological breakthroughs or unique design features have VEOWARE's innovative gyroscopes introduced to the space industry?**

When we created the company, we aimed at launching an earth observation satellite constellation flying at very low orbit altitude (250-300kms). Rapidly, we discovered that we would need a lot of agility that only Control Moment Gyroscopes (CMG) can provide. However, no CMG for the targeted size of platform where available and more than that, the available CMG price was not affordable for commercial applications. We then decided to develop a CMG and started to review our business model.

Our CMG is compact and modular. Each CMG module contains the power and control electronics, they can work independently in a cluster as a building block. Mechanically, we have pushed the parameters to the limit. The flywheel is running up to 10000rpm, while dissipating only 1.5W. The very high speed of the flywheel is also an advantage regarding micro vibration.

**What sets VEOWARE's gyroscopes apart from traditional gyroscopic technology, particularly concerning precision, durability, or adaptability to space conditions?**

I would say, flywheel speed, cost, lead time and simplicity. Regarding cost and simplicity, several technologies and control approaches have been implemented to reduce the cost of components used without reducing the reliability. For example, the torque precision is similar to reaction wheel performance while not using extreme performance gimbal angular sensor.

**Can you discuss any advancements or trends in space mechanism engineering that you find particularly exciting or promising for the future of space exploration?**

Robotics arm, these mechanism remained customized mechanism for some specific missions, mainly scientific missions. There is now a coming need to standardize and commercialize affordable and reliable robotic arms for in-orbit servicing (docking, repairing, assembling, etc). This is clearly a direction Veoware wants to follow.

**Given the demanding nature of space exploration, what advancements do you think are necessary in the field of ball bearings and mechanisms to further improve the reliability and efficiency of space systems?**

It is now clear for us, after discovering our bearing cage instability issue, that bearing cage dynamics understanding is mandatory for any mechanism containing high speed rotating parts.

**What were the key technical challenges encountered in developing RWA's and gyroscopes for space applications, and how did VEOWARE address them?**

One of the key technical challenge was to select and size bearings configuration for 2 different type of applications in the same system. The gimbal stage is rotating at low speed but needs to be very rigid as it is carrying the most of the system mass while the

flywheel shall rotate at very high speed with limited dissipation (friction). The strategy of Veoware was to use Component Off The Shelf bearings to limit the cost and have acceptable lead time. At the end of the product development and during the qualification test campaign, we noticed a weird noice randomly appearing from the flywheel. After long investigation we were suspecting a bearing cage activity. We were advised by ESA to contact APO-GEE to further investigate this issue. APO-GEE helped us to confirm the root cause and to propose a solution. Fortunately, we succeeded to point the issue during our qualification test campaign and not later. This issue is inducing very bad performance in micro vibration.

**From your perspective, what are the main technological challenges in designing**

**RWA and gyroscopes that can withstand the evolution of space mechanisms, and how do you envision addressing these challenges in the future?**

Excluding radiation aspect at avionics level, the main challenge when designing reaction wheels and CMG is to limit drastically the jitter. On one side, huge effort on continuing to reduce the rotor balancing grade are foreseen. We continue to improve the control performance. And finally we would like to work more with partners having expertise in bearing dynamics to always make the best design choices.

**In terms of future innovation, what do you envision as the key areas of focus at VEOWARE?**

With our developed mechanism and avionics building blocks, we would like to propose a full Guidance and navigation system and become leader in orbit motion control with the vision to enable in-orbit assembly.

**How does VEOWARE foster a culture of innovation and entrepreneurship within the organization? Are there any unique strategies or practices that have contributed to the company's success?**

The classical approach of test-as-you-fly is possible with relatively small mechanisms. In this case, they fit in a vacuum chamber where the temperature can be adapted to simulate the in-orbit conditions. Unfortunately, this is not possible when you need to test large deployable mechanisms like a large deployable antenna of 12 meters diameter (like in Biomass). This is particularly true for the deployment in space. In this case, the qualification approach to the space environment is based on the following:

- Test in relevant environment (typically cold and vacuum) at component level
- Build a simulation model of the complete large deployable mechanism that includes also the test rig
- Correlate the simulation model with a deployment test of the complete large deployable mechanism in ambient, including the influence of the test rig
- Use the correlated simulation model with the test data obtained from the tests at component level, removing the influence of the test rig, to evaluate the actual deployment behavior in space environment.

Tests facilities exist in Europe where a large deployable mechanism or structure can be tested. The ESA ESTEC large space simulator is a good example. However, the problem of deploying in cold and vacuum on ground is the test rig that needs to offload the gravity. The design and testing of the test rig might have a complexity and associated cost almost like the item to test. This is why, normally, the test rig is designed to only work in ambient. That is significantly cheaper and efficient.

# I'm calculating. So I am?

**Checkmate to human intelligence?**

In May 1997, Gary Kasparov, the greatest chess player of the last century, suffered a historic defeat. It's not just the defeat itself that matters, but the nature of the opponent: Kasparov admitted defeat against Deeper Blue, the supercomputer developed by IBM to defeat the chess grandmaster. The world shook; the machine triumphed over the man in a game thought to encapsulate human intelligence. A tipping point was definitively crossed, seemingly with no possibility of return.

Thought has long been equated with calculation. With the famous aphorism, "Reason is nothing but calculation," philosopher Thomas Hobbes, a contemporary of René Descartes, restricted rationality to calculating thought alone. According to this logic, everything is arithmetic and planning; the human mind is a mechanism, a calculating machine.

At this point, what is surprising about Kasparov's defeat? On one hand, a man whose skills as a strategist and planner can be summed up by evaluating two positions per second. On the other, a 1.4-ton silicon monster equipped with 256 processors, capable of estimating 300 million positions in the same period. Does that mean that we shall conclude that man is outdated or obsolete?

Fig. 1 - Garry Kasparow, World Chess Champion

That is far from certain.

Kasparov was defeated, but by a single point, a gap equivalent to losing one game in all six games. Isn't that the salient point? There was a game! Therefore, despite the defeat, would we not see in this event the opposite confirmation of what was necessary at first glance, namely, that human ingenuity remains inaccessible to the most formidable machine, however complex it may be?

**Check to the King ChatGPT**

A quarter of a century later, let us acknowledge that the paradigm has advanced even further. Despite the performance of Deeper Blue, it should be pointed out that the latter was limited to manipulating data marked by the algorithm, scrupulously following the roadmap that its designers had drawn for it; in short, the work of a large calculator.

This is no longer the case with the recent evolution of artificial intelligence, known as generative intelligence. The advent of the faculty of representation, coupled with machine learning and networks of "artificial neurons," now gives systems the possibility to manipulate complex subjects, work on their development, and deliver analytical results in remarkably elaborate terms, all using methods hitherto reserved for humans. Anyone who has ever approached ChatGPT could only feel a certain amazement. From the production of sharp texts to the writing of computer codes, passing through the most mundane conversations, the difference with Stanley Kubrick's HAL seems minimal. Artificial intelligence uses statistical and probabilistic approaches to reverse the best outcome. According to such criteria, competition seems lost: when it comes to the ordering of elementary bricks, a human being will never again be able to compete with the computer.

Yes, but... what would happen if, by chance, no combination of these basic elements could produce the desired result? How would King ChatGPT act if, after exhausting all possibilities, no solution appeared to him? He would give up, invariably.

**A narrow mind**

ChatGPT remains irretrievably subject to man. And for good reason: the entity was formed by man, to respond to man, and, above all, to remain walled between the barriers imposed by man. The term "machine learning" does not hide the eminently restricted framework within which ChatGPT operates. Because, despite the myriad means at his disposal, it is by nature impossible for him to "learn" outside the limits set for him. He performs, unconsciously; he continues the tasks communicated by the invitation of command, without discerning the slightest meaning; ChatGPT calculates, without the slightest doubt.

The limitations run deep. By way of illustration, let's confront artificial intelligence with

Fig. 2 - AI remains subject to man

a problem that we know well: ball bearing cage instability[1]. In this example, let's take the reasoning a step further and postulate the existence of a version 2.0 of ChatGPT, which would allow the establishment of mathematical models, as advanced as desired. As we could do with an engineer, let's imagine that we submit the following question to him: "Could you completely describe the movement of a ball bearing cage in a mathematical way, in order to study the phenomenon of instability of the cage?" What would come out of it? First of all, ChatGPT 2.0 would offer highly complex modeling, integrating extremely precise physical laws and an almost perfect resolution of the equations of the mechanical equilibrium of the cage. Then, he would use the model thus generated to study the movement itself, depending on the parameters of the problem: geometry of the cage, operation of the bearing, initial conditions, etc. All this without ever reaching a satisfactory conclusion!

The reason? We asked him a question that had no valid answer. The nature of the movement of the ball bearing cage is inherently chaotic[2]. This means that any prediction based exclusively on mathematics cannot be considered, independently of any other consideration. Thus trapped in its symbolic straitjacket, ChatGPT will fail.

APO-GEE went beyond this framework to solve the cage instability problem. Drawing the necessary conclusions, we took note of the particular essence of the movement of the cage. From there, we abandoned raw calculation in favor of identifying the physical mechanisms that govern unstable phase entries. How? By perceiving the absurdity of hitting the wall of mathematical chaos, by weaving links between the situation and the goal we were pursuing, by accepting to jump into the unknown, by sometimes making mistakes, by often inventing, by also doubting... In a word: by summoning our humanity.

**Game over**

The game lost by Kasparov, resulting in the loss of the point necessary to defeat the machine, was lost following a brilliant move, worthy of the greatest chess masters. The originality was such that the maneuver completely destabilized the Russian champion. The move in question was also widely commented on in schools and enthusiast circles, as the brilliance of the tangle of cables and integrated circuits left its mark.

Could we have been wrong? Have engineers finally discovered the keys to human intuition, an expression no longer sounding like a pleonasm? Years later, it would turn out that Kasparov's fatal blow was actually the result of a computer bug.

The error is human. Genius too.

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1 See our article: "What is cage instability?" available on the APO-GEE’s website (www.apo-gee.tech)

2 See our article: "Mastering chaos" available on the APO-GEE’s website (www.apo-gee.tech)

# About APO-GEE

APO-GEE is the Belgian deep-tech start-up specialized in ball bearing engineering.

APO-GEE helps space agencies, satellites launch companies, aircraft manufacturers, defense contractors and equipment manufacturers, with innovative products and dedicated high value services related to ball bearings used in harsh environments and severe conditions.

APO-GEE'S tools and methods have also proven to be highly effective for high demanding applications in other sectors and industries (medical techs, machine-tools or automotive).

APO-GEE is driven by innovation and IP development. The Butterfly Cage (unconditionally stable cage), the Cobweb Bearing (smoothest functioning high speed bearing) and APO-GEE's unique computational tools are real breakthroughs in the bearing world.

APO-GEE is located in the Liège Science Park, Belgium, in a premium environment dedicated to deep-tech start-ups.

**www.apo-gee.tech**