# APO-GEE TALK

## Innovative thinking for ball bearing engineering

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ESA (ESTEC)

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BALL BEARING ENGINEERING

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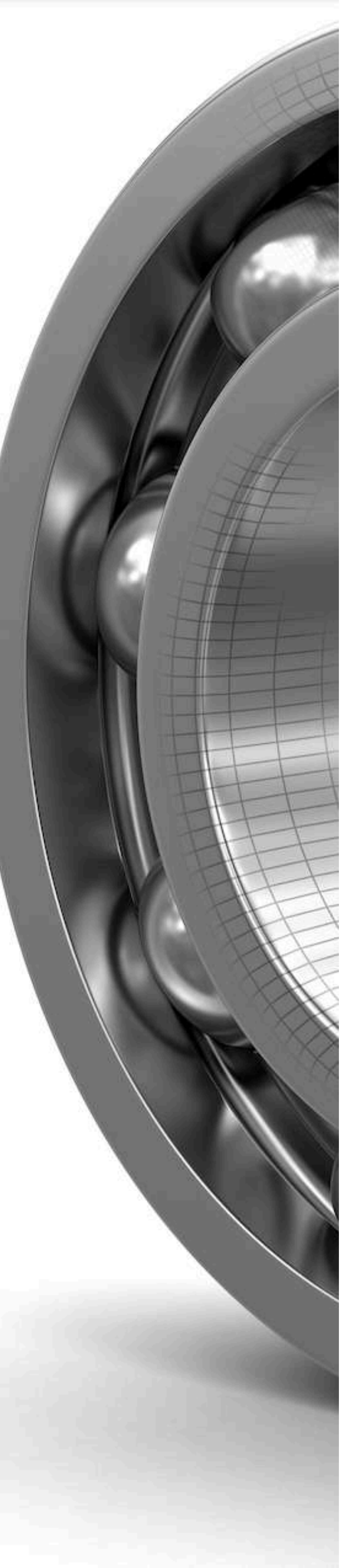

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# Editorial

Dear Readers,

Welcome to the second issue of our technical magazine, where we delve deeper into the fascinating realm of ball bearing engineering. Our goal with this magazine continues to center around providing you with our latest insights, advancements, and applications in this dynamic field.

In the realm of "Ball Bearing Physics," we dive into an article that demystifies the phenomenon of ball speed variation. In the "Trends" section, we embark on a journey of technological transfer where you will discover how innovations pioneered in space exploration are finding their way into terrestrial applications. In the heart of the "Engineering" segment, we tackle a perplexing and persistent issue that has confounded engineers for years: the rattling bearing noise problem in machine tool spindles.

Our pages then come alive with an exclusive interview with Massimo Palladino, an accomplished engineer at the European Space Agency. As we delve into his remarkable journey, we explore his responsibilities encompassing space mechanisms and pyrotechnics. This conversation offers a unique glimpse into the mind of a visionary engineer driving innovation and pragmatism on multiple fronts.

In the "Vision and Perspective" section, we cast our gaze toward the past and the future. Explore an article that delves into the boundless world of scientific advancement.

In closing, we would like to express our gratitude to you, readers, who continue to make this magazine a beacon of innovation and inspiration. We hope that this second issue captivates your imagination and serves as a catalyst for further exploration and advancement in the exciting field of ball bearing engineering.

Enjoy the read!

Sincerely,

Sébastien Assouad
CEO APO-GEE

# On the Ball Speed Variation Phenomenon

In general, although many bearings operating at high speeds are mainly subjected to a predominant axial load, it cannot be excluded that a parasitic radial force or a misalignment torque come into play.

Cases in point are legion. For example, a pump impeller of a high-speed cryogenic turbo-pump cannot have a perfectly equitable distribution of pressure on the periphery of its volute. It is therefore likely to endure a significant radial force, in addition to the axial component. In the same vein, even if the bearings of spindles of machine tools are mounted with an axial preload, a significant radial load induced by the use of the device could lead to an asymmetry in the loading of the bearings.

This asymmetric loading, i.e. when the presence of a radial force or a misalignment torque is denoted, is not without consequence on the operation of the bearing. The kinematics of each ball is actually disrupted. Thus, by looking at what happens on the average radius of the bearing, on the path taken by the balls, it can be seen that the balls do not move at constant speed around the bearing. This phenomenon is called **ball speed variation**.

The appearance of ball speed variation is not without consequence; the bearings that are subjected to it see their lifespan suddenly shortened with, sometimes, dramatic consequences as a result. Sketching the outlines is therefore a necessity, in order to prevent any potential disastrous failure.

**Understand the phenomenon**

To try to explain the physics of the ball speed variation, it seems useful to examine the situation of the balls within the bearing.

Let's first imagine a bearing that is preloaded in the axial direction, as used in many assemblies. Such conditions imply a symmetrical distribution of the balls around the axis of the bearing. This configuration is shown in Fig. 1, by means of a cross-section of the bearing. As announced, the contact angles $\phi_1$ and $\phi_2$ of two diametrically opposed balls are equal. Direct consequence: if the bearing rotates, the self rotational speeds $\omega_1$ and $\omega_2$ of the balls are equal. So the balls rotate at the same speed around the axis of the bearing.

What happens if a misalignment torque is superimposed on this axial preload? In this case, the balls deviate from their initial symmetry and their contact angle changes according to their position on the circumference of the bearing. Fig. 2 indeed shows that the two diametrically opposed balls now have very different contact angles $\phi_1$ and $\phi_2$. However, if these angles differ, the kinematics of the two balls represented can no longer remain identical. Conclusion: the balls no longer rotate at a constant speed around the axis of the bearing. This is the so-called **ball speed variation**.

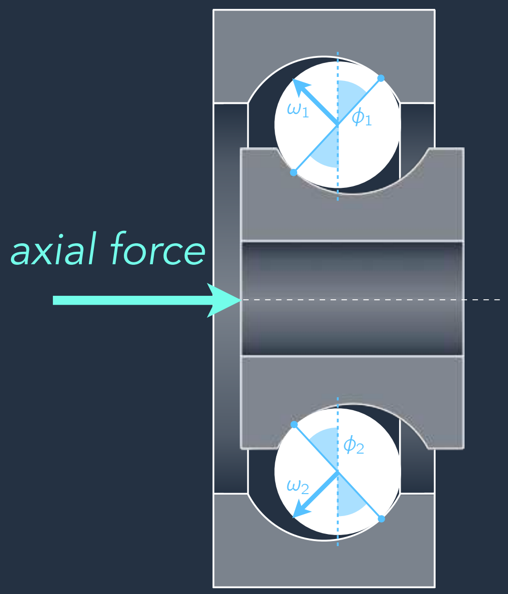



Fig. 1 – Symmetric loading

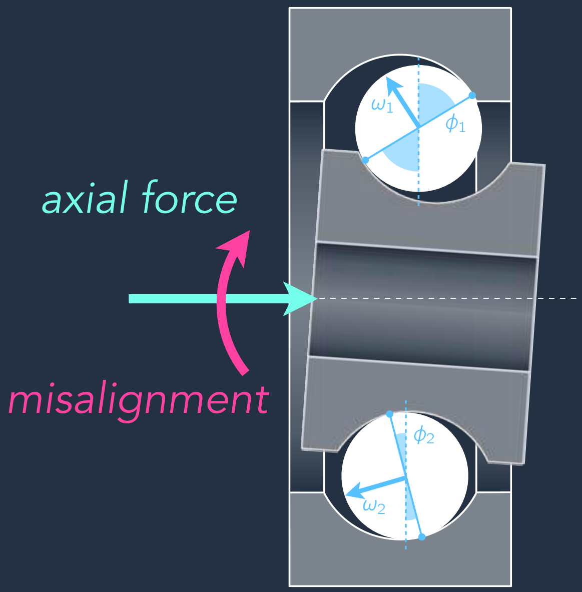



Fig. 2 – Asymmetric loading

In what way could these marginal disturbances constitute a subject of concern?

To understand it, we need to follow a ball in a bearing that is loaded with a combined load and compare its bumpy path to its symmetrical counterpart. Fig. 3 shows the different phases of a complete rotation of two balls around the axis of the bearing. The white ball moves at a constant speed (symmetrical load case) while the colored ball has its speed that fluctuates (asymmetrical load case). Suppose that the two balls start at the same time from the top (1) and that the colored ball has a higher initial speed (2). It is first caught up with the white ball (3), then overtaken by the

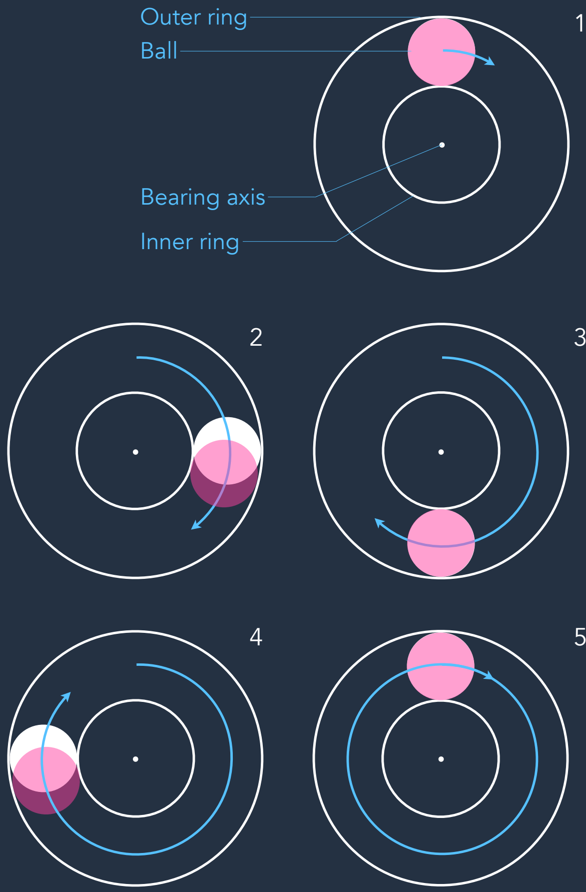



Fig. 3 – Motion of a ball, comparison between symmetric and asymmetric loadings

**Where is the problem?**

The speed of the balls varies over the entire periphery of the bearing. But, in the end, is it so worrying? After all, the bearing is an object of revolution. From then on, all the balls end up going through the same states, slightly out of phase with each other.

latter (4), before joining it in turn at the end of the cycle (5). Indeed, since the two bearings move at the same rotational frequency, the average displacement of the colored ball must equal that of the white ball.

**OK. But there is still no problem!**

The balls seem to adapt naturally and without any apparent major constraint to the loads, even if they are asymmetrical. But what about the cage?

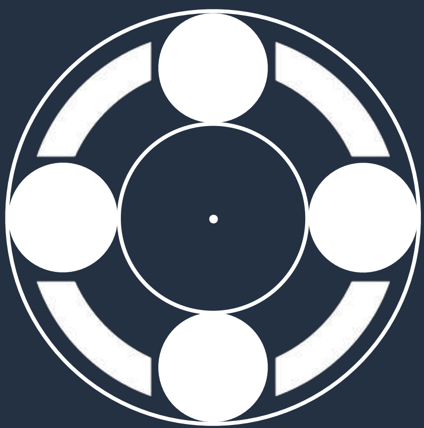


Fig. 4 - Cage of a symmetrically loaded bearing

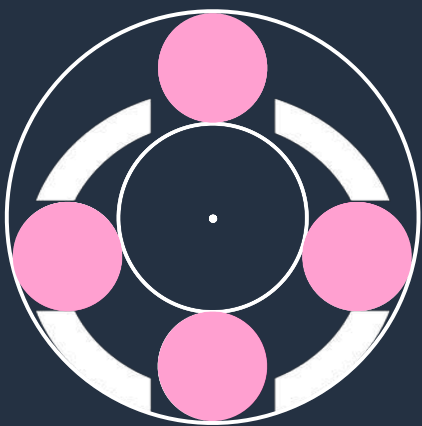


Fig. 5 - Cage of an asymmetrically loaded bearing

The symmetric load case does not affect the cage in any way. If the cage is correctly designed, it evolves freely between the balls and the rings of the bearing. Fig. 4 illustrates this for a simplified bearing comprising four balls. On the other hand, the kinematics imposed on the balls in the case of a combined loading singularly changes the situation. In fact, the clearances of the cage are quickly taken up, so that the balls compress the separator against the guiding ring, as shown in Fig. 5 for this same bearing of four balls. However, no separator can withstand the terrible constraints induced by the phenomenon.

APO-GEE has developed a new ball bearing adapted to difficult load conditions: the COBWEB bearing. Its objective is to counteract the effects of misalignment and to offer an alternative to existing products. Thus, this new bearing is able to accommodate a combination of axial and radial loads, just like deep groove and angular contact bearings, while improving the tolerable misalignment. The key lies in its ability to smooth the movement of the balls, which drastically reduces contact angle variations all around the bearing.

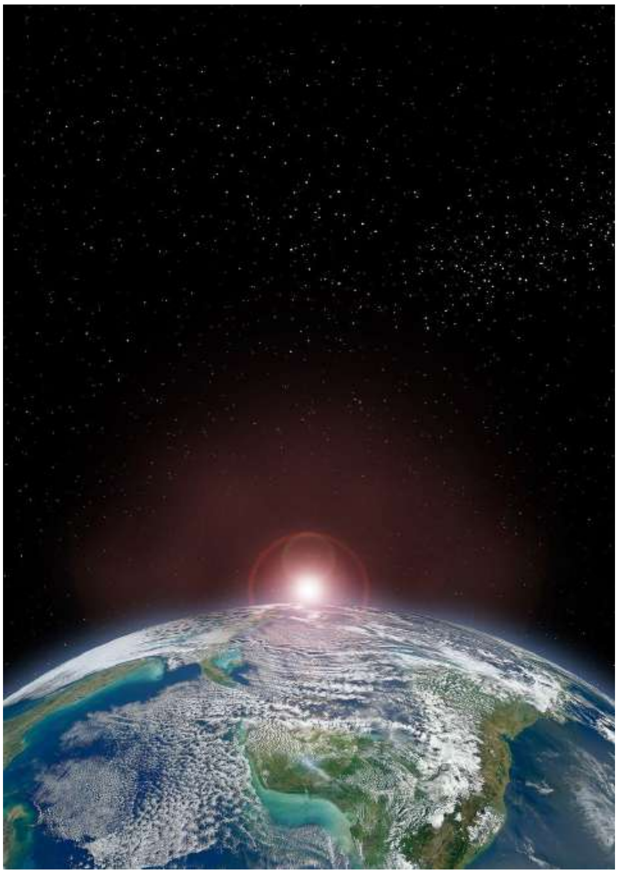
Christophe Servais
CTO APO-GEE

# Transferring Ball Bearing Technologies From Space to Terrestrial Applications: Advancements and Applications

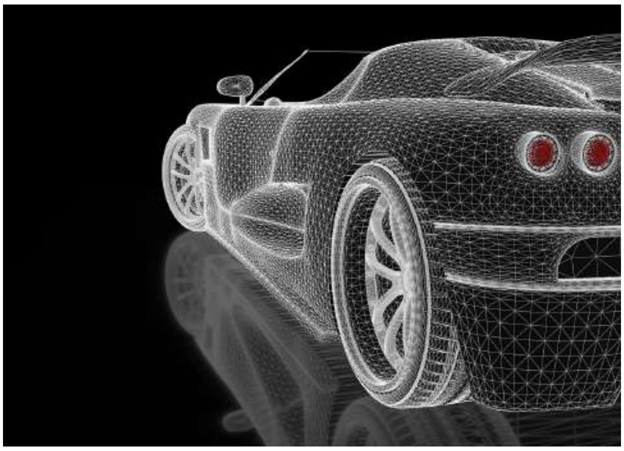
In the same way that Formula 1 technologies have been transferred to conventional cars, space technologies serve as a remarkable laboratory and contribute to progress in numerous terrestrial applications. Ball bearings are a prime example of how space technologies have paved the way for innovation.

Ball bearings used in aerospace applications must adapt to extremely complex operational conditions and harsh environments, including high speeds, the absence of atmosphere, extreme temperatures, nearly impossible maintenance operations, and the requirement for high reliability over extended periods.

These challenging constraints have undeniably stimulated research and innovation.



A significant example of technology transfer from space to other industries lies in solving the problem of cage instability. This issue has long been known in the aerospace industry, involving erratic movement of the cage that can lead to disastrous consequences, especially in reaction wheels used in satellites or space probes. Despite extensive documentation over several decades, a fully satisfactory solution had remained elusive. However, a decade-long research endeavor, focusing on understanding the phenomenon of cage instability and mechanisms that governs it, has recently resulted in a complete resolution. An unconditionally stable cage has been developed, proving its efficacy through both mathematical analysis and strong experimental validation, even under extreme tribological conditions. This innovative technology, initially designed for successful aerospace missions, can now be seamlessly adapted to other industrial contexts. The world of machine tools is a perfect example where this technology finds practical application. The cage developed for aerospace ap-



plications effectively addresses the issue of rattling noise encountered in machine tool spindles. It provides a swift and concrete solution to an evident problem of unpredictable noise and vibrations.

Another example is the high-speed bearing. Historically, achieving high speeds required mechanical engineers to make challenging compromises in ball bearing design. Furthermore, at high speeds, the proper functioning of a bearing depends not only on its resistance to fatigue (directly related to maximum contact pressure) but also on its ability to limit heat dissipation, prevent thermal instability, and ensure good cage behavior. This challenge is especially critical in the context of turbo pumps of rocket launchers, which rotate at very high speeds. This particular issue has led to groundbreaking research and innovation, resulting in the creation of the Cobweb bearing. It enables an ultra precise and reliable operation, marking a significant breakthrough in the field of bearings. While the Cobweb bearing is particularly suitable for turbo pumps, its application can be extended to other high-speed applications or those requiring more precise and smoother operation, even under extreme combinations of loads and/or speeds. Consequently, this new bearing technology represents a genuine advancement for dental milling machines operating at very high speeds (up to 500,000 RPM). Here, too, lies a perfect example of technology transfer.

The combination of those technologies developed for space, can also provide a concrete response to the challenges posed by the advent of electric vehicles. The bearings used in these vehicles must meet new paradigms in terms of noise, vibrations, and speeds to ensure an optimal driving experience. This synergy of technologies can offer reliable and high-performance solutions to meet the ever-increasing demands of the automotive industry concerning sustainability and technical performance.

In conclusion, transferring space technologies to terrestrial applications, particularly in the realm of ball bearings, has proven immensely beneficial. The challenges posed by space environments have fueled research and innovation, leading to revolutionary solutions that address issues not only in aerospace but also in various other industries. These technology transfers exemplify how advancements made for space exploration can be leveraged to enhance efficiency, reliability, and performance in applications closer to home.

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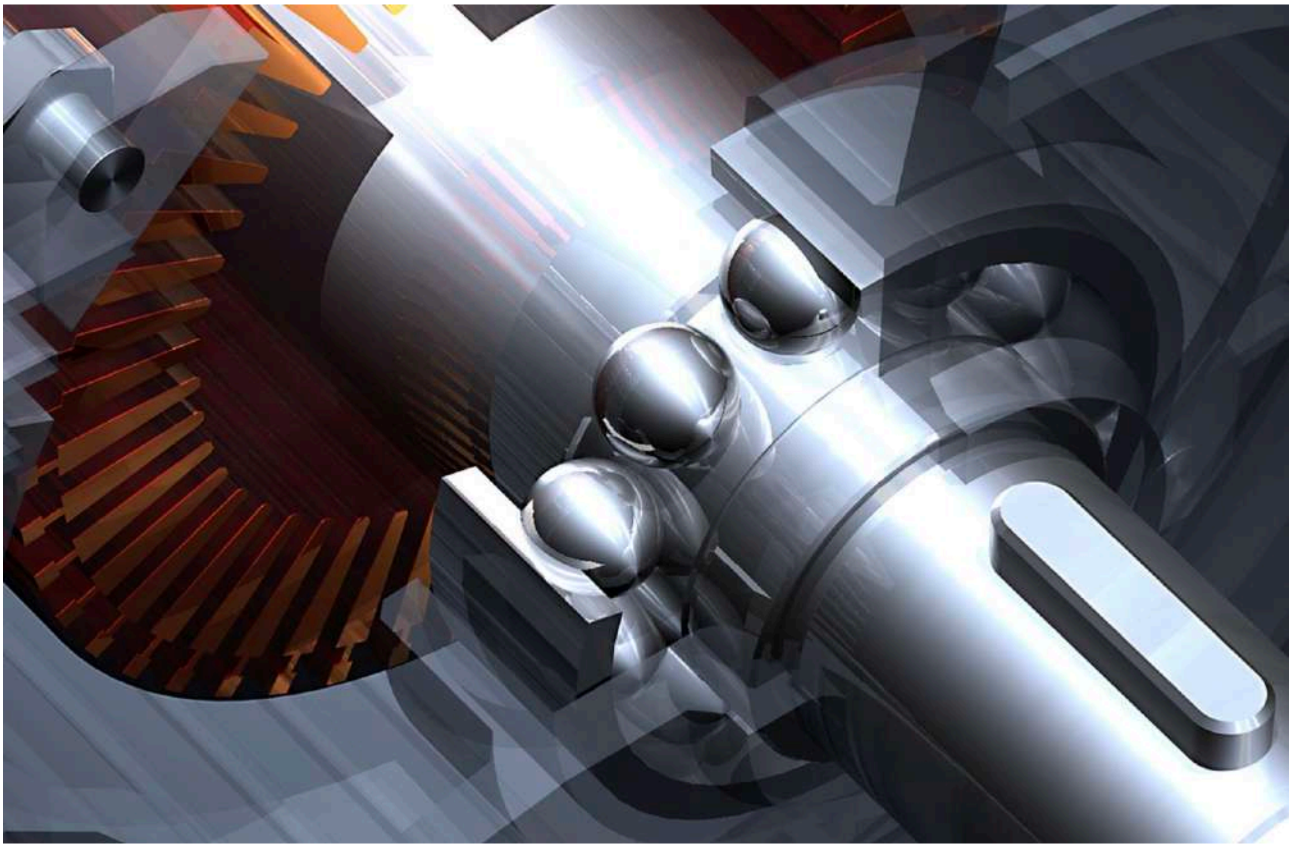
# Silencing Machine Tools: Solving the Rattling Bearing Noise Problem in Spindles



**An innovative concrete solution to this misunderstood long-standing problem**

In the world of precision engineering, machine tool spindles serve as the backbone of countless industries, enabling the creation of intricate components with utmost accuracy. However, lurking within these critical components lies a persistent issue: noise and vibrations originating from ball bearings. As essential elements in spindle design, ball bearings are prone to generating disruptive noise and vibrations that can significantly impact performance, quality, comfort and operational efficiency.

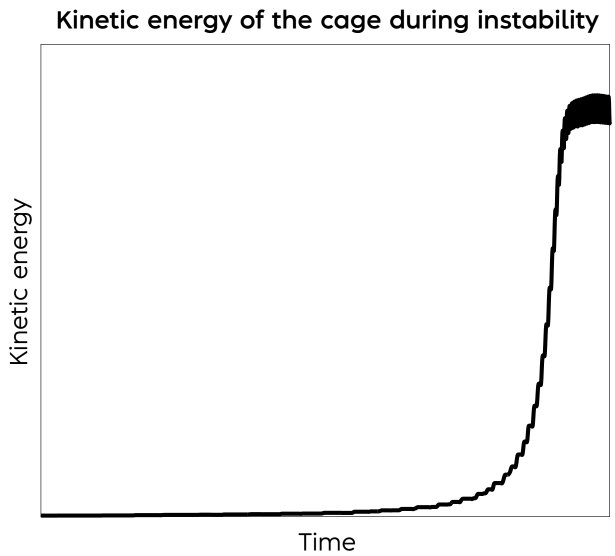
More particularly, one of the primary challenges is the occurrence of a sudden and strong increase in noise, often called rattling or squealing noise in the industry, which generates vibrations and which can be both alarming and disruptive to the machining process. Surprisingly, this kind of noise is hard to predict and can occur unexpectedly even when the spindles have new bearings installed. Furthermore, it is not limited to high-speed operations, as it can also manifest at lower speeds. Also, the bearing spindle can rattle like crazy even under the lightest loads, exacerbating the issue. Thus unpredictable and disruptive noise occurrence poses significant challenges that necessitate thorough investigation and innovative solutions to maintain the smooth operation and performance of machine tool spindles.

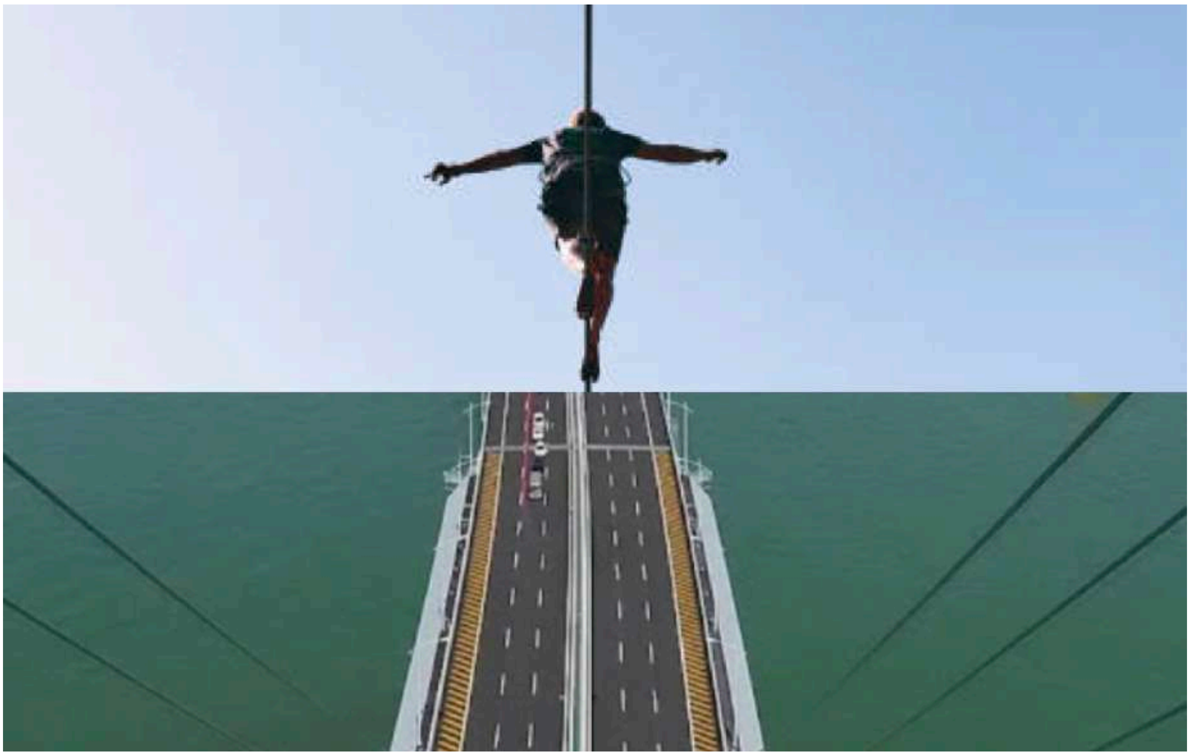
This article aims to delve into the depths of this problem, shedding light on the causes, implications, and most importantly, a concrete innovative solution to tackle the predicament of the rattling noise in ball bearings for machine tool spindles.

**Rattling noise: unfortunate consequences and unsatisfactory solutions so far**

The rattling noise can have significant consequences that affect both productivity and operational efficiency. One possible consequence is the increase in machine tool downtimes. When the noise becomes pronounced, it may necessitate the machine to be shut down for investigation and repairs, leading to undesirable delays in production schedules. Moreover, the occurrence of such noise demands more maintenance efforts and constraints. In some cases, this may even require the replacement of (relatively) new bearings! Furthermore, the repercussions extend beyond the manufacturing process, potentially leading to postponed customer technical acceptance or even end customer claims. The uncertainty associated with the noise problem, as it may occur intermittently, adds an element of unpredictability and unwanted costs. Additionally, it is crucial to acknowledge that the noise has also an impact on operator well-being.

When it comes to coping with this rattling noise in machine tool spindles, the general recommendations often emphasize the importance of proper maintenance practices. Regular inspection, lubrication, and alignment checks are highly recommended to identify and address any potential issues before they escalate into a more significant problem. Additionally, replacing the bearing, even if it is relatively new or almost new, is sometimes suggested as a potential solution. However, despite these recommendations, it is worth noting that these solutions may not always be satisfactory. In some cases, even after following rigorous maintenance practices and replacing the bearings, the rattling noise may persist or still occur later, leading to frustration and ongoing challenges. This indicates that the underlying causes of the noise may be more complex and require a new approach to achieve a long-lasting solution.





The Butterfly cage guarantees an operational « window of stability » wider than any ball bearing design

**The real cause of the problem: the cage instability phenomenon**

Despite ongoing efforts, the persistent challenge of finding a solution to the rattling noise problem remains. One of the primary reasons for this is the poor understanding of the underlying phenomenon itself. Its elusive nature made it challenging to pinpoint the exact causes and develop an effective resolving strategy. Moreover, the fact that the noise appears randomly adds another layer of difficulty. In fact, it was even difficult to provide a definitive name for this specific noise.

The problem has a name: the phenomenon of cage instability.

Contrary to the world of machine tools, this is a well-known and documented phenomenon in space applications, at the level of gyroscopes or reaction wheels for instance. Which has also remained without solutions for several decades. Until now.

The cage instability phenomenon involves a sudden and significant increase in the kinetic energy of the cage, which results in an abrupt and pronounced disturbance. The energy involved in this phenomenon is exceptionally high, causing a hula hoop movement of the cage, also called cage whirl. Remarkably, the speed of this whirl can reach up to hundred times the rotating speed of the bearing. What sets this phenomenon apart is its distinct « on/off » characteristic, differentiating it from the gradual noise generated by normal bearing degradation. In the same way that this behavior was difficult to predict and characterize for space applications, it was also difficult to apprehend in the context of machine tools. Once again, until now.

Many parameters have an impact on the cage instability, so a small change in the geometry and/or in the working conditions can make a « good » cage become a « bad » cage. The cage stability can be compared to that of a tightrope walker. With conventional bearing designs, it is as if the path to stability is extremely narrow. It doesn't take much for the walker to fall into the void or the bearing to tip it into instability.

It is important to mention that instability should not be confused with other phenomena. A well-conducted frequency analysis for instance shows that the phenomenon of instability generates characteristic frequencies. These ones are very different from the typical failing frequencies associated to ball bearings (ball pass frequencies on both inner and outer races, ball spin frequency and fundamental train frequency). And with far greater powers.

**A breakthrough in ball bearing engineering: an new unconditionally stable cage**

While the current solutions for limiting noise and vibrations in ball bearings for machine tool spindles have their limitations, we made a real breakthrough. Through a comprehensive understanding of ball bearing kinematics, an innovative approach and original computational modeling tools, we discovered precisely the mechanisms that govern cage instability. This has proven pivotal in finding a concrete solution: the Butterfly cage, a new unconditionally stable cage for which a patent is pending.

For the first time it is possible to explain what we hear in front of a machine in a situation of rattling or squealing noise, or what we see on frequency analysis. For the first time, it is possible to have a truly appropriate solution. If we take the analogy of the tightrope walker again, a bearing equipped with a Butterfly cage no longer evolves on the rope of instability, it has a highway of stability in front of it.

The solution is robust, directly applicable, and does not require any changes to the spindle assembly.

Our knowledge has been validated both mathematically and experimentally. And our unconditionally stable cages have been validated for aerospace applications for which the operational conditions are even more restrictive than those of machine tools.

By harnessing deep understanding of ball bearing physics and the phenomenon of cage instability on the basis of 12+ years of intensive research, a concrete solution has emerged to solve the problem of noise and associated vibrations in ball bearings for machine tool spindles. This breakthrough not only enhances the performance of machine tool spindles but also sets a new standard for precision engineering.

What is your next step now?

SA & CS

# Massimo Palladino

**Mechanisms System Engineer, ESA**
ESA-ESTEC, The Netherlands
Massimo.Palladino@esa.int

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

I started my professional career at ESA as a YGT (Young Graduate Trainee) in 1999. I was at that time integrated in the ATV (Automated Transfer Vehicle) team. I was mainly performing analysis in the area of structures and mechanisms. After the YGT. I moved to Safran (at that time Snecma) where I worked at Techspace Aero (currently Safran Aero Boosters). I left Safran for ESA in 2007 while I was in charge of solving complex mechanical problems mainly on aircrafts. I came back to ESA ESTEC (the Netherlands) in the mechanisms section. Until March 2023, I was in charge of several developments in the frame of mechanisms and pyrotechnics. This involved satellites and launchers applications. Particularly the fact of solving critical issues on Ariane 6 resulted in bringing me to ESA HQ Daumesnil (in Paris, France) to help in the final phases of the Ariane 6 development. My responsibilities, in the frame of Ariane 6, are to ensure that the mechanical and thermal systems work and interact properly. This includes inevitably an appropriate design and functional performance of ball bearings particularly in the turbo and motor pumps as they operate at very high speed.

**Can you describe a project you've been working on related to space mechanisms?**

**What were the main challenges and how did you overcome them?**

A typical challenge for space mechanisms is to operate in the harsh space environment. An example is the deployment of large structures in space. On the GAIA mission, there was the need to deploy a sunshield of about 12 meters diameter. When the test on-ground, simulating the space environment, took place, the sunshield did not even move after the release of the hold down mechanisms. Deep investigations and analysis performed at ESA ESTEC concluded that there was a severe impact of the cold and vacuum conditions that resulted in an increase of about an order of magnitude of the resistive loads. It was concluded that a design modification (inclusion of electrical motors to help in the deployment) was needed. Thanks to the tests at component level (to characterize the physical phenomena) and the analysis performed (to evaluate the design modifications), the GAIA sunshield successfully deployed in space and resulted in GAIA still operating well after 10 years in orbit.

**How does collaboration with other engineering disciplines play a role in your work, especially in multi-disciplinary projects within a space agency?**

Mechanisms engineering is about system engineering. Indeed, it includes structural engineering to make sure the mechanism resists to vibrations and shock at launch. It includes thermal engineering because you need to build a mechanism that can survive the harsh space environment. It includes also control engineering as most of the mechanism must move to a defined position with very high accuracy and stability. That explains why presently I oversee both the mechanical and thermal systems on Ariane 6.

**How do you ensure the reliability of ball bearings in space applications, considering the extreme conditions they might face?**

The classical method is to refer to the mechanisms ECSS (European Cooperation for Space Standardization) that defines severity factors to be applied in the design and testing of ball bearings. These factors are based on statistics considering worst cases based on 3 sigma values. Some of these factors are applied for example on the resistive torque or on the expected life to be demonstrated by test. However, ball bearings, even if they are used in many applications since a long time, hide secrets that are still very difficult to understand. One main critical component of a ball bearing is the cage that separates the balls. It is a known fact that most of the ball bearings suppliers do not do a specific design of the cage. The cage is in fact designed most of times based on empiric rules. These rules are grounded on a trial-and-error basis. This has the consequence that it is very difficult to estimate some reliability of the cage performance. Usually, for launchers, most of the turbo pumps and motor pumps ball bearings cages are designed by trial and error. The methodology used consists in testing the ball bearings in extreme conditions (increasing friction for example) to verify experimentally that the cage behaves still in a stable fashion. Even if the problem of cage instability for turbo

pumps may be sometimes considered solved, my personal and technical advice is to use the code from Apo-Gee, which has been partly developed through an ESA R&D activity and that has been recently connected to the commercial software for ball bearing design CABARET, also through an ESA contract. This Apo-Gee code, validated with extensive tests performed at the ESA tribology laboratory (European Space Tribology Laboratory), allows simulating much more cases than what it is possible by test. It allows deriving stability maps that would finally provide the robustness and reliability required for a ball bearing operating in a complex space mission, be it a launcher or satellite.

**What do you see as the most significant challenges facing the field of Mechanical and Aerospace Engineering in the next decade?**

A challenge that is more and more required is the life of a mechanism. The SADM (Solar Array Drive Mechanism) of Sentinel3 had a requirement for continuous rotation during minimum 7.5 years aiming at 12.5 years. It is in orbit since 2015. Considering that, for mass reduction purposes, the tendency is to use a lighter motor with a large multiplication stage, the required life for the motor ball bearings becomes extremely high (some billion revolutions for Sentinel3). Ensuring the robustness and the reliability of the ball bearings at end of life is really challenging.

**Could you share a specific example of a design innovation or breakthrough you've been involved in that significantly improved the efficiency or functionality of a space mechanism?**

Pyrotechnics mechanisms apart, for which a breakthrough has been the pyrotechnics valve on board the Juice mission, that required an extensive life in the very harsh Jupiter environment before being actuated, another real breakthrough is, in my view, the code developed with Apo-Gee to design a robust and reliable ball bearing cage. In addition, this code has allowed Apo-Gee to invent an intrinsically stable cage that would basically extend the stability map to pretty much every possible operational regime of the ball bearing. This would be highly beneficial for several ESA projects being launcher or satellite.

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

A trend that is very interesting is of course to get rid of contact elements inside a mechanism. For example, the replacement of ball bearings by flexural pivots has certainly a very big interest even if it is very challenging, as it has been experienced with the flip mirror mechanism of Sentinel3. The best way to replace contact elements is to go for fully contactless technologies like levitation wheels or magnetic gears. However, the present position of many projects is that these technologies are not yet fully mature. Pursuing the contactless technologies development is a priority for ESA, to prepare future projects maybe in a 10-year lifespan.

**What safety considerations are taken into account when designing and testing**

**space mechanisms to prevent any potential hazards during launch, deployment, or operation?**

When speaking about safety, I directly think about pyrotechnics mechanisms. Indeed, there is an office in the ESA launch base located in Kourou (French Guyana), that is particularly focussed on safety. This office analyses principally the pyrotechnics mechanisms as they might create some hazards that can be catastrophic especially in case of an unwanted actuation of some launcher mechanisms like igniters. The main consideration is to make sure that these mechanisms are not actuated by mistake by an operator or by a natural event like a lightening for example. This is done in several ways. First, there is a test performed to make sure that some spurious current or excitation (a shock for example) does not trigger the mechanism. Also, for mechanisms that might create a catastrophic event, there is a specific mechanical or optical barrier (on Ariane 6 for example) to prevent an unwanted actuation. Finally, to protect from the lightning (frequent in Kourou), there is some specific electrical continuity requirement that is verified by test.

**Can you explain the process of validating and testing space mechanisms on Earth to ensure their performance in the space environment? What are some of the key testing facilities and techniques used?**

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.

# Aberrations

The evolution of man is inseparable from that of technology. How could it be otherwise? How to respond to this Darwinian obligation without creating, without improving again and again these innumerable tools which mark out the line of time of humanity? How to continually adapt to such a hostile environment, devoid of the slightest utensil and of this precious energy whose importance cannot be more appreciated than today?

But that requires sacrifice. In particular: time, a lot of time. Because such a tropism imposes a lot of hard work before tasting the joys of discovery and the advantages it confers. The most extraordinary inventions have never cut it.

Take the example of what revolutionized a whole section of the history of science: the astronomical telescope. The latter indeed marked a turning point in the study of the cosmos: for the first time since Aristotle, we had an instrument other than the naked eye to contemplate the sky.

Galileo began his observations, whose impact we know, around the time the first telescope appeared. He perfected it at the margins and made his own observations. However, he did not theorize anything about the optical laws used; he worked empirically, only.

Kepler, who admired the work of Galileo, continued his work. Convinced that he could improve the refracting telescope, he tried to establish mathematical rules to describe the behavior of light within this new instrument. He did not manage to do so, but he touched on this crucial point: how to push the limits of this marvelous invention if we do not identify the cogs?

The brilliant and obsessive Huygens answered this question, but by proceeding differently. Where his illustrious predecessors were content to manipulate, move and triturate their lenses, Huygens went much further. He was indeed the first to really identify and describe the real functioning of a

telescope. Without him, optics would not have developed and we would have continued to progress gropingly, playing with lenses, without rules and without a guide. In short, without understanding.

He thus refined the contours of the diopter to establish the laws that govern the positioning and sizing of the lenses of an astronomical telescope. In particular, he succeeded in resolving with precision the geometric aberration from which the instrument suffered, the very one at the origin of the vagueness surrounding the mystery of the "handles" of Saturn reported by Galileo. His brilliant mind led him to size and assemble the lenses like no one had been able to do before. Meticulous and aware that the manufacture required a care at least as crucial as his reasoning on paper, Huygens went so far as to develop himself the methods of polishing the glasses he used.

This mastery led the Dutchman to unparalleled image sharpness and magnification, which notably led him to the first observation of Titan, as well as to the deduction of the structure of Saturn's rings. Moreover, Huygens himself recognized it: he owed his discoveries to his telescope.

And yet, what must have been his frustration! Huygens had enough to realize the dream set in motion by Descartes: the perfect refracting telescope. Alas, despite his knowledge, the scientist has hit a wall. The much-sought-for perfection actually required a lens shape significantly different from the sphere, totally unachievable by seventeenth-century manufacturing techniques. He therefore had to make do with assemblies of traditional diopters.

Astronomical telescopes, even rudimentary, have led to an exponential increase in our knowledge of the stars. But in this world where all the cosmos remained to be discovered, what would have been the influence of Huygens if he had not known similar technical limitations? Despite his sensational discoveries, could we not imagine that they would have been even more fantastic if he had had the means to materialize his concepts? If the extreme finesse of manufacturing lenses of our time had been accessible to Huygens, what frontiers would he have been able to push back?

APO-GEE has invented a new ball bearing geometry, the COBWEB bearing, capable of correcting malfunctions related to combined loading and high rotational speed. APO-GEE has, among other things, highlighted the fundamental physical principles at the heart of the problems encountered, in order to derive a technological solution from them that effectively counters ball speed variation as well as friction losses. Still unimaginable a few decades ago, the complex production of this new bearing is now made possible by modern shaping techniques.

Bearings also have their geometric aberrations. We are working to fix them.

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# 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 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 (medtechs, 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**