APO-GEE TALK

Innovative thinking for ball bearing engineering

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Interview
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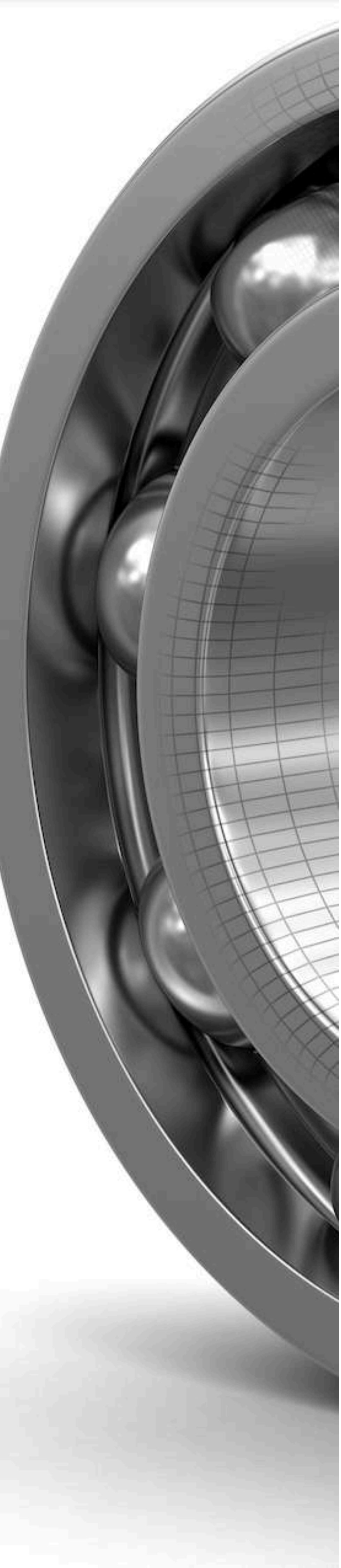

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Editorial

Dear Readers,

It is my great pleasure to welcome you to the inaugural issue of our new magazine, focused on the exciting and ever-evolving world of ball bearing engineering.

As you know, ball bearings play a critical role in a vast range of industries. These simple yet mighty components help to minimize friction and enable smooth, reliable operation in countless applications.

However, despite their ubiquity and importance, ball bearings also present a range of engineering challenges that must be addressed in order to achieve optimal performance and durability. From material selection and design optimization to lubrication and corrosion resistance, Ball bearing engineering is a complex and fascinating field that requires constant innovation and improvement.

That is why we have launched this magazine: to provide a platform for our latest research, insights, and developments related to ball bearing engineering, with a strong focus on aerospace and defense applications.

Our aim is to make a contribution, certainly not to claim that we know everything. We are not experts in materials, nor specialists in lubrication for example. Our focus remains the optimization of designs, through an original approach and an in-depth knowledge of bearing physics based on more than 12 years of research. In this sense, we are always excited to learn and seek synergies with the other technical disciplines surrounding bearing innovation.

I hope you find this issue informative, engaging, and thought-provoking. Our goal is to provide a valuable resource for all those who are passionate about ball bearing engineering and its potential to drive innovation and progress across industries. We welcome your feedback and suggestions (sas@apo-gee.tech), and look forward to continuing this journey together.

Sincerely,

Sébastien Assouad
CEO APO-GEE

Cage instability
Predict the unpredictable? No.
Prevent the unpredictable? Yes!

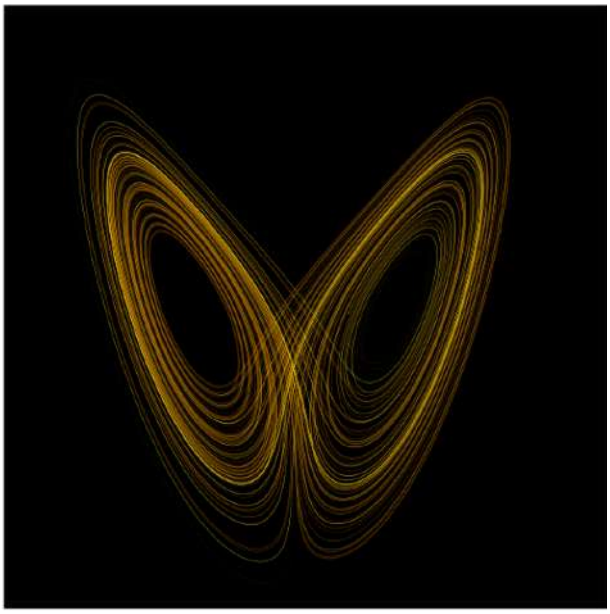
If the mathematician Henri Poincaré were still among us, he would find that the cage instability phenomenon in bearings fits perfectly into his new physical paradigm: chaos.

Cage instability is a frequent issue, which is encountered in many space applications. Like lightning, it is the appearance of a physical phenomenon that is as sudden as it is unpredictable. In a fraction of a second, the kinetic energy of this small ring, which is simply in charge to correctly separate the balls around the bearing, rises instantaneously without any kind of apparent trigger. This increase in the energy is materialized by a hula-hoop motion of the cage between the balls, exactly as it would be for a circus artist. But contrary to the enjoyment produced by the latter, the hula-hoop of a cage leads to real disasters. We are thinking of the many space missions that have been aborted as a result of this phenomenon.

Cage instability was identified quite soon after the beginning of space conquest, by the major actors of the space domain from all over the world. The engineers of the time, seeing their mechanical assemblies suffer from such evils, did try to look for a solution. In vain… However, they were able to measure the vibrations and the strong increase in the torque that was generated by cage instability. Also, they had sometimes to see the separators failing within their bearings. Unfortunately, the root cause of the problem remained a mystery. And yet, engineers spared no effort! Indeed, in addition to numerous experiment studies, a lot of new sophisticated mathematical model developments have been carried out during the last decades. Their common point? Their purpose: to reproduce the motion of the cage with the highest possible fidelity.

How is that possible? How can we imagine that much resources were not sufficient to solve this cage instability issue? How can we imagine that engineers and scientists who sent men to the Moon could not establish what could possibly trigger the deleterious hula-hoop? The answer comes from the paradox that is introduced by the very nature of the problem itself: cage instability is a chaotic phenomenon, therefore inherently unpredictable.

Predicting the unexpected… At least, we have an explanation about this admission of failure! But we are not out of the woods yet…



Picture credit Wikipedia

The notion of chaos touches on a science that everyone is familiar with, if only because of the impact of its results on their daily lives: meteorology. Who has never been surprised by a rain shower, when the weather forecast predicted a generous sunshine? Such a misadventure could have led some of us to a simplistic conclusion: from the obvious difference between reality and forecast, are we not facing a purely random phenomenon? The answer, though counterintuitive, is firm: no.

The physical laws that govern the weather are deterministic, like those that dictates the trajectory of the apple falling from the three. Nevertheless, unlike the latter example, the complexity of the physical description of the atmosphere implies an extreme sensitivity to the initial conditions. These can be seen as the snapshot of the situation at the present time, on which any computational simulation is based. All this was beautifully summarized by the meteorologist Edward Lorenz, who was a pioneer regarding chaos: "Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?". Understand: a chaotic system, from a mathematical point of view, although based on deterministic laws, will remain unpredictable. This is not because the system is random, but because the initial conditions will never be known with sufficient accuracy.

Based on this fundamental observation, we have chosen to proceed differently. We actually reversed the reasoning and started our investigation with the conclusion: we will never be able to establish **when** a cage will be unstable, but we can establish **why** a cage is unstable ; meteorologists will never been able to establish **when** the lightening will strike, but they can establish **why** lightening strikes. If the storm rages, if the lightening flashes, it is because we observe cumulonimbus in the sky. Our role was to find the cumulonimbus associated with the cage. But contrary to meteorologists, we could possibly act on the design of the cage to avoid the troubles.

And we did it, so that no cloud could settle.

Christophe Servais
CTO APO-GEE

When ChatGPT is wrong

When asking ChatGPT in March 23 how to limit cage instability effects in ball bearings, you may have this kind of answers:

1. Using hardened steel cages to increase their resistance to deformation
2. Maintaining high precision during bearing assembly to ensure uniform load distribution on the cage
3. Using ball bearings with metal or synthetic cages to increase resistance to shocks
4. Adjusting the preload or radial clearance of the bearing to improve stability

If we look at these elements, force is to note that Chat GPT, is quite wrong :

Regarding 1. « Using hardened steel cages », improvements in material properties could increase the strength of the cage, but they won't affect cage dynamics (or marginally)!

Regarding 2. « Maintaining high precision during bearing assembly », decreasing the misalignment would protect the cage against the ball speed variation phenomenon, not against cage instability!

Regarding 3. « Using metal or synthetic cages », the resistance of the cage could be increased, but the propensity to be unstable would remain.

Regarding 4. « Adjusting the preload or radial clearance », indeed, the preload has an effect on instability. But which one Mr. ChatGPT?

Those means proposed by ChatGPT will thus at best, somewhat limit the effects of cage instability.

APO-GEE's innovative Butterfly cage does not limit cage instability. The Butterfly cage PREVENTS cage instability to occur!

SA

Challenges of cryogenic turbopump engineering

Technological advances in a growing market

The increase of investments of space nations, the growing number of missions, the trend towards re- use, increased efforts to reduce carbon footprint, and the development of space tourism are all factors driving the the launch vehicle engines and spacecraft market.
Although growth in this market will continue to be strong in the coming years, the challenge facing the engine industry will remain considerable, namely to reduce development costs and increase performance, while ensuring the reliability of future engines.
Technological advances are, of course, key here. These technological advances include the use of alternative fluids that make easier the fuel handling and the improvement of production processes through additive manufacturing. Innovation has thus opened up new opportunities, translated in terms of cost optimization, although trade-offs still need to be considered in terms of performance.

Reliability of turbopumps

But innovation must also be expressed in maintaining and improving reliability. Reliability, and by corollary safety when it comes to manned flights, cannot be compromised. Despite many years of intense developments, problems remain with regard to ball bearings used in turbopumps. These remain a major element of cryogenic engines, and it is clear that many problems encountered in recent decades have not yet been able to find a satisfactory answer. Launchers have experienced extremely damaging failures, in particular due to thermal instabilities within the bearings of the turbopumps, cage instability or even ball speed variation phenomena. A sudden increase in temperature in a cryogenic bearing when the level of friction becomes too high, is a major problem that can lead to the destruction of the bearing. Temperature increase must be taken into account.
However, given the size of the stakes in financial, technical and even political terms, associated with the development of new engines, it is essential to provide new solutions at the turbopump bearings level, which will guarantee their reliability.

Limitations of the « catalog » approach and innovative ball bearing engineering

If innovation in the field of turbopump ball bearings has been very limited or non-existent so far, let us first remain realistic: it will not result in new mechanical concepts that will replace the bearing. But even if it is a relatively simple mechanical element, the phenomena that govern its operation in the extreme conditions encountered in turbopumps are still largely unknown.

Innovation therefore comes from the understanding of the physical phenomena that govern the operation of bearings. At the heart of these. Because deep understanding leads to appropriate solutions.

Indeed, the "off-the-shelf approach", which consists of selecting a bearing from a catalog based on the sizing on the one hand, and the loads on the other, clearly has its limits. The selection of the bearing in this case is indeed essentially focused on fatigue in connection with the lifespan of the bearing. However, fatigue and lifespan are not the determining factors in the choice of a cryo-bearing for a turbopump. The « catalog » approach also does not provide information on the behavior of the bearing itself. This is reflected in particular by the absence of data concerning its internal geometry. However, this internal geometry plays a decisive role in the good performance of cryogenic bearings.

Where the "catalog" approach has shown its limits, an innovative characterization method based on a power criterion to achieve bearing equilibrium opens new perspectives. It leads directly to innovative bearing designs that provide concrete answers to the most critical applications. And turbopumps are a perfect example of this.

Classical modeling based on Newtonian dynamics does not allow accurate bearing equilibrium to be achieved. The one based on the power criterion definitely can. In particular, it makes it possible to understand the basics of sudden temperature rises in cryo-bearings, and to take into account the age instability or Ball Speed Variation phenomena, that can lead to the rupture of the bearing. And that's a major step forward.

Concretely

The way forward is therefore to be able, via modeling, to have a precise idea of what is happening at the heart of the bearing of a turbopump with regard to potential bad behavior: thermal instability, cage instability, ball speed variation, power dissipation by friction...

Based on an analysis of data relating to operating conditions, lifespan, sizing and loads, the engineering process must ultimately lead to a new design of the elements making up the bearing, to ensure its increased reliability; being understood that the good behavior of the bearing is not limited to the resistance to fatigue.

The engineering process will vary depending on the input data. If the problem is specific, in other words, if the problem has already been highlighted on a bearing that has already been selected, the engineering will first consist in modeling its behavior via characterization tools that are based on the power criterion. An optimized design will be deduced from this, which can be experimentally validated before implementation in operational conditions.

If the problem to be addressed is broader, i.e. when defining a turbopump bearing « from scratch », the engineering process will be iterative. The new design will be achieved through an approach that will first rely on a good understanding of the bearing environment and its operating conditions. On this basis, a first modeling exercise will be carried out to lead to a first selection of bearings. Tests will be then carried out on a dedicated bench and optimization will follow at different levels (e.g. towards cage instability or thermal instability). The optimization will again be subject to experimental validation.

In both cases, the aim will be to identify the operating limits of the bearings, particularly according to the loads, and to determine the elements of design that will ensure their proper performance.

In both cases, effective and open collaboration between the motor designer, the partner in charge of bearing engineering, the possible bearing manufacturer, and the person responsible for the test infrastructure, will remain essential.

Conclusion

In the aerospace industry, preventing problems will always be more effective and less expensive than solving them. And turbopump bearings are no exception.

The bad news is that a deep understanding of what goes on inside the bearings of turbopumps cannot be dispensed with in new engine development programs. The good news is that when it is carried out in an innovative, precise and rigorous way, it directly contributes to ensuring the success of these programs, and to sustaining the related investments. And certainly also, to ensure a decisive competitive advantage for the actors who will engage in the process.

What is your next step now?

SA

Raffaella Sesana

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What inspired you to pursue a career in Mechanical and Aerospace Engineering, and what do you find most rewarding about teaching and research in this field?

Mechanics has been my "first love" since I was a child. I used to play with Lego bricks and Meccano kits, to disassemble and reassemble home appliances... Actually, I think that teaching and research are rewarding occupations: they do not allow you to get old, as both are curiosity driven. Every day starts with new answers to look for. And mechanics somehow models a sort of "order", a relation between causes and effects which can help interpreting everyday life... Remembering my passion and the difficulties that I lived in forwarding my career in STEM, today I try to encourage young women and non-men to pursue this career and to support them in the process.

What research projects are you currently working on, and how do you envision them impacting the field of ball bearings and Mechanical and Aerospace Engineering?

An innovative field I am working on is the application on thermographic analysis to material and components characterization, in particular relating to fatigue damage, to wear, to residual stresses, to microstructural aspects. Non-destructive full field and non-

contact assessment of physical and mechanical properties of bearing components can contribute to improve the reliability of components and to develop safety procedures for operators and users.

Can you discuss any collaborations you have had with industry, and how these collaborations have impacted your research?

The research group* I am in collaborates with many Companies but, talking about ball bearings, a consolidated research activity is developed with Tsubaki Nakashima. Thanks to this collaboration, we investigated research fields which allowed the Company to have focused resources for research, and to the University research group to be connected to applied research, in particular, on components impacting everyday life for everybody. This last issue is very important for us because it allows both parts to participate with an open minded and free approach to research topics.

How do you integrate research into your teaching?

This is the best part, actually... When I discuss lectures with students, the one part is dedicated to theory, models, equations... but when case studies are described, students are immediately interested. The application of theory to real cases, and also mentioning open questions not yet solved by research is actually very stimulating. Another integration comes from showing in classes broken parts. Broken parts always trigger questions and discussion, this forces me to look for answers and cope with new point of view. And also to validate my teaching performance I always say that we learn more from failures than from successes. As mentioned before, this can be referred to life too...

How do you address challenges in teaching Mechanical and Aerospace Engineering, such as changing industry demands?

The first challenge is for me, to select among industry demands what of them will be the best in terms of education, learning, research outcomes and innovation. During lectures, I introduce students to open questions, to actual problems and research topics. When the students "respond" to these stimulations, my approach is to vehiculate and follow their activity in research so that a reciprocal continuous exchange between University and Company is assessed.

What do you see as the most significant challenges facing the field of Mechanical and Aerospace Engineering in the next decade, and how are you preparing your students to address these challenges?

My teaching is related to basics of mechanics. My approach is to provide the students with the base analytical and experimental "tools" to approach any challenge.

I think that innovation in the field of aerospace will require a deep structural reflection on the role that aviation has in our society, a reflection which has to go in the direction of strong and real sustainability goals. Therefore we need to make meaningful research towards sustainability of the sector and focus on the needs that only aviation can fulfil, such as long distance intercontinental travels and which other means of transport cannot perform. For other means of transportation, research in Mechanical Engineering can strongly contribute towards sustainable and fast mobility.

*https://www.dimeas.polito.it/en/research/research_groups/design_and_experimenta8on_of_mechanical_drive_components_-thermography_and_damping_materials

Model or not model

Abstraction, the engine of all science

Opposing abstraction and experimentation, as is too often done, is forgetting that these two components are two sides of the same coin. Every model needs to be tested against experimentation to have a chance of representing reality. Conversely, any experimentation cannot acquire legitimacy unless it has been fundamentally first constructed through abstraction, followed by an objective analysis of the results produced. Consequently, experimentation feeds modeling, and vice versa. However, even with this truth in mind, the abstract component of engineering remains too often flouted.

Abstraction is, nevertheless, essential to the development of any science. Mathematical models, from the simplest to the most complicated, have been used for millennia. Their role? Helping mankind in its journey towards a better understanding of nature, in the broadest sense. As a sign of the power they give to scientists, mathematics have, over time, taken an increasingly important place in the development of science. Until we reached the turning point that appeared a few decades ago: the birth of the computer.

The advent of computing: towards ever more sophistication

Before the computer, the insolubility of systems of equations that were too complex led generations of scientists to simplify their description, until they tended towards mathematical representations that could be solved (from Pierre-Simon de Laplace's description of the Solar System to the sending of men to the Moon). Fundamentally, the entire process was under control. For example, studying the apple falling from the tree is a simple law, from the concepts manipulated (force = mass x acceleration) to the methods necessary for their resolution (differential equations).

But the new capabilities offered by the advent of computing have considerably reoriented the way a model can be conceived. Regardless of the emergence of artificial intelligence, of which we currently only glimpse an infinitesimal portion of the consequences on our future lives, the computing power of computers has quickly led to ever more detailed descriptions of physical systems to be studied. Nowadays, the scientist moves from problems he can solve "by hand" to problems requiring huge amounts of operations (algorithms), often requiring several days or even several weeks of computation time.

Sophistication: the flip side of the coin

Does this mean that we are inexorably moving towards a finer representation of reality? Not so sure. The opportunity to introduce ever more refinement into a model is particularly attractive. But it is not without risk. Indeed, if it appears tempting to increase without limit the finesse of the laws used, constantly increasing the number of parameters means also multiplying the difficulties accordingly. Moreover, all of this comes with a loss of control by the physicist or engineer over the methods of resolution, which are increasingly beyond the user of the new computational tools.

In such circumstances, how can we still distinguish error from uncertainty?

APO-GEE's position

Modeling is a valuable tool, as long as it is preserved from excessive sophistication. Furthermore, it must be constantly confronted with reality, by feeding on precise experimental data.

In this way, we develop advanced calculation tools that are targeted and limited to the specificities of the problems being addressed. In this way, we limit ourselves to what needs to be modeled, avoiding losing control and, above all, losing ourselves. we do not seek to quantify at any cost, but rather to understand, surely. Identifying and understanding physical phenomena summarize our tropism.

An example?

Let's imagine a very particular problem to deal with: cage instability. How to proceed? Establish the most complete model possible in order to ultimately achieve the ultimate goal, which is a panoptic vision of all the parameters that govern cage instability? No, it's actually the opposite.

We reversed the approach and started with a set of questions and answers: Why does a cage become unstable? Because its kinetic

energy suddenly increases! How can the cage increase its energy? By moving in a coherent manner within the bearing, so as to continuously increase its speed!

We had a clear line here: build a model that allows us to reproduce this coherent movement of the cage between the rings and balls of the bearing, so that its causes become clear to us.

We managed to build such a model, focused on this phenomenon of instability; we identified the mechanisms that lead to unstable phase, or what gives this deleterious coherence to the movement of the cage; we understood, physically, why this cage could behave so problematically and erratically; we confronted all of our results with experimentation; and ultimately, we invented a remedy based on the knowledge generated.

So, model or not model? That is the equation!

CS

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 provides engineering tailor-made solutions so that aerospace missions and defense projects are no longer dependent on ball bearing failure.

APO-GEE is driven by innovation and IP development. The Butterfly Cage, the Cobweb Bearing and APO-GEE's unique computational tools are real breakthroughs in the bearings 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

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