

APO-GEE TALK

SPECIAL EDITION:

How space bearing innovation
boosts spindle performance
and transforms precision machining



APO-GEE
BALL BEARING ENGINEERING

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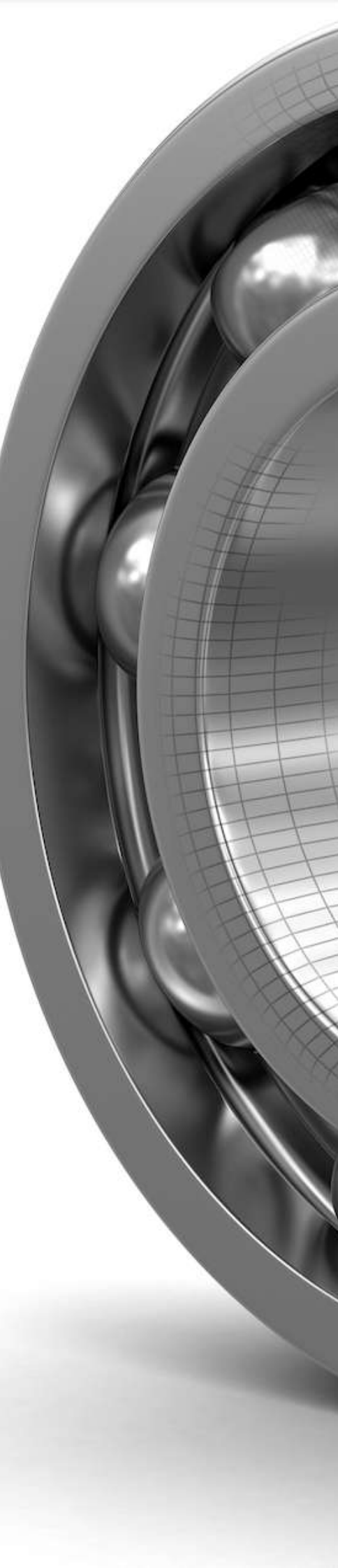


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How space bearing innovation boosts spindle performance and transforms precision machining

1. Introduction

The spindle market is becoming increasingly demanding. Manufacturers require bearings that are not only more precise, but also capable of delivering higher performance and greater added value. As spindles evolve to operate under ever more extreme conditions, the role of the bearing has never been more critical.

Over the past years, several technological developments have indeed improved bearing performance. However, these improvements have been largely incremental, fine-tuning existing concepts rather than redefining the performance frontier.

The key question is: **can we move beyond incremental steps and envision significant leaps in spindle bearing performance?** The answer is yes. Such disruptive innova-

tion exists today, rooted in the stringent requirements of the most demanding aerospace applications. These technologies, once developed for space, have now reached full maturity and are ready to transform the performance landscape of spindle applications.



This report will first outline the main trends and requirements shaping today's spindle and spindle bearing markets. It will then examine the recent developments in bearing design and their inherent limitations. From there, it will demonstrate, in very concrete terms, how breakthrough innovations such as the **Butterfly cage** and the **Cobweb bearing** address the critical challenges of noise, vibration, and speed, delivering performance levels never achieved before in spindle applications.

2. Trends in machine-tool spindles

In modern machine tools, spindle performance requirements have become increasingly demanding. Higher rotational speeds are sought after to shorten cycle times, enable **high-speed machining**, and ultimately boost overall productivity. In sectors such as mold making, aerospace, and medical components for example, spindles are expected to reach extreme speeds while maintaining stability. At the same time, precision and stiffness are critical, since even the slightest deviation in rotation, whether vibration or eccentricity, translates directly into surface finish errors or dimensional inaccuracies on the workpiece.

Flexibility is another key expectation. A single spindle often has to perform a wide range of operations, from high-speed grinding and milling to turning and heavier cutting processes, which means it must accommodate very different types of loading: radial, axial, and combined.

Finally, users demand durability and **reliability**, as spindles represent a major investment. They must deliver predictable, stable performance with minimal maintenance, while managing thermal variations effectively in order to prevent dimensional drift and maintain machining accuracy.

Speed, versatility, and reliability are therefore the guiding principles shaping the evolution of the machine tool spindle market.

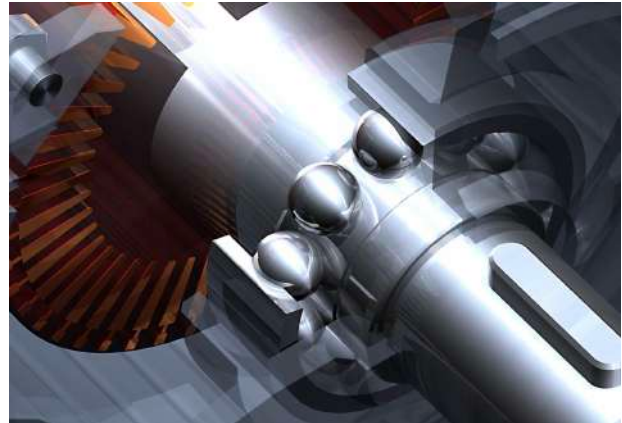


Fig. 1 – Spindle bearing

3. Trends in precision bearings for machine-tool spindles

Ball bearings have naturally evolved to meet the performance trends. Translating spindle performance requirements into bearing specifications has led manufacturers to push forward in several technical directions.

To enable higher speeds, precision angular contact ball bearings are increasingly built in hybrid configurations, using ceramic balls with steel rings to reduce inertia, limit heat generation, and extend life at extreme DN values. Advanced materials are widely adopted to minimize friction and thermal rise. Bearings are produced to the highest tolerance classes with superfinished raceways. Contact angles are selected carefully, lower value for high-speed applications and higher values when axial rigidity is required.

As durability and thermal stability remain critical, advanced coatings are employed to resist fatigue and wear, while lubrication

strategies help to control temperature rise and extend service life.

In recent years, however, it is clear that most advances have focused on materials, surface finish, and lubrication technologies, yielding only **marginal or incremental performance gains**.

By contrast, very little change has been made in terms of **design**. There is a widespread belief that, when it comes to bearing geometry, everything has already been invented and that future improvements can only be incremental.

The remainder of this report will demonstrate that this assumption is incorrect: significant design innovations are still possible and can deliver substantial enhancements to spindle performance.

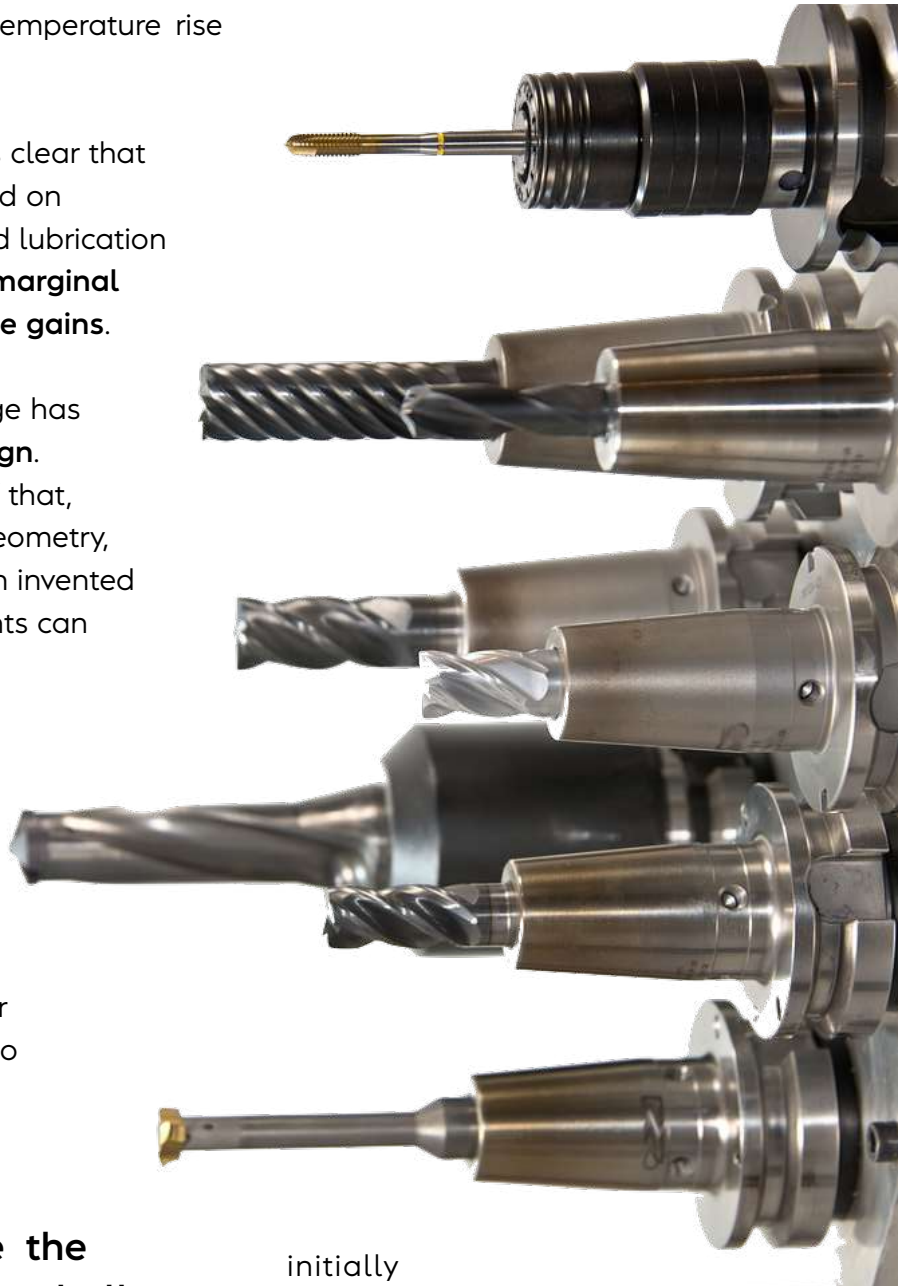
4. How to overcome the noise and vibration challenge

The advent of the Butterfly cage

The only component free from any mechanical constraints in a spindle

Every mechanism aims to convert one type of motion into another, transforming mechanical variables into different forces, torques, or velocities. All mechanisms share a common feature: they interact with

initially independent bodies. It is the mechanical designer's task to create connections that constrain the parts of an assembly to move according to a predetermined pattern. By imposing various types of contact, restricting relative movement brings the desired motion to life. In all cases, mechanical parts slide, roll, or mesh to ultimately produce the intended effect.



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Spindles follow the same principles. They all mechanically link a series of bodies with utmost precision through physical contact to ensure precise tool guidance for maximum machining accuracy. With one exception: the **ball bearing CAGE**.

A ball bearing creates a kinematic connection between bodies rotating relative to each other. The rings and balls, pressed against each other, ensure controlled guidance of the assembly incorporating the bearing. However, the separation of the balls requires a cage, which has no constraints whatsoever, the clearances between the rolling elements grant it complete **freedom of movement**.

This leads to a surprising conclusion: the ball bearing cage is a singularity, an oddity, the **only component in a mechanism free from mechanical constraints in a spindle**.

Due to its freedom of movement, the cage inevitably induces **BACKGROUND NOISE** and therefore **micro-vibrations**. Even if often inaudible to the human ear, these disturbances can negatively impact machining precision. Doesn't this unique condition deserve special attention?

Beyond the background noise, the cage instability or « rattling noise » issue

Most spindle manufacturers have been facing, for years, an unexpected problem of random or entirely unforeseen noise and vibrations, often referred to as **rattling noise**. This can occur even in new or relatively new bearings, with significant conse-

quences for performance, customer perception, maintenance costs, and downtime. In some cases, it may even necessitate the replacement of nearly new or new bearings.

The rattling noise is actually a manifestation of **bearing cage instability**, a well-documented phenomenon in space applications for example. Despite decades of efforts, it has not been possible to completely eliminate, or even reliably predict, this issue. This is particularly regrettable because high-precision bearings, which incorporate ceramic balls and precisely machined rings, are high-value components whose performance can be severely compromised by cage instability.

The intermittent nature of rattling noise adds **unpredictability** and **hidden costs**. To manage it in machine tool spindles, conventional recommendations focus on rigorous maintenance practices: regular inspection, lubrication, and alignment checks. Replacing the bearing, even if relatively new, is sometimes suggested. However, these measures are not always effective. In some cases, noise persists despite meticulous maintenance and replacement, indicating that the underlying cause is more complex and requires a fundamentally new approach.

One major reason for the difficulty in addressing this problem is the limited understanding of the phenomenon itself. Its elusive nature has made it challenging to pinpoint causes and devise effective solutions. This phenomenon has been extensively studied in space engineering, particularly in gyroscopes and reaction wheels, where it

was critical and remained unsolved for decades, until recently.

Cage instability in spindles is characterized by a sudden, large increase in the kinetic energy of the cage, producing an abrupt, pronounced disturbance. The energy involved is exceptionally high, causing the cage to exhibit a **hula hoop motion**, or **cage whirl**, which can reach speeds up to 100 times the bearing's rolling speed. Unlike gradual noise from bearing wear, this phenomenon has a distinct **On/Off** behavior, which makes it unpredictable and difficult to characterize, similar to its historical challenges in space applications.

Cage instability is **chaotic** in nature: minor changes in operating conditions (speed, friction, load, etc.) or slight variations in cage geometry can trigger it. Numerous parameters influence this phenomenon, and its unpredictable character means that testing extreme or limit cases cannot guaran-

tee reliable future performance. Cage stability can be compared to a tightrope walker: with conventional bearing designs, the path to stability is extremely narrow, and even slight deviations can lead to failure.

It is also important to note that the **frequency signature** of cage instability is entirely distinct from the system's natural frequencies and from classical bearing failure frequencies (ball pass frequencies, ball spin frequency, and fundamental train frequency), and it manifests with much greater energy.

The Butterfly cage

By deeply understanding the cage's dynamic behavior, APO-GEE has developed a groundbreaking solution: the **Butterfly cage**. This innovative design not only **prevents instability** but also significantly **reduces background noise** and micro-vibrations compared to any conventional design, regardless of the application.

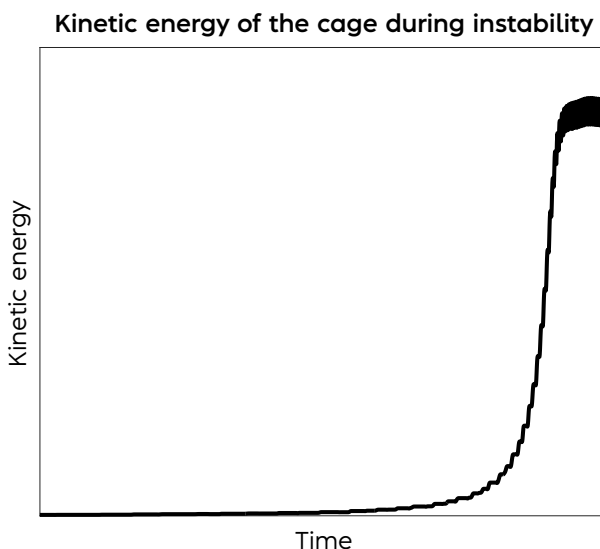


Fig. 2 – Cage instability is caused by a sudden and significant increase in kinetic energy.

Originally developed to address cage instability in space applications (reaction wheels, gyroscopes, turbo-pumps), the Butterfly cage now integrates seamlessly into machine-tool spindle bearings. Its value and performance, first proven in space and now in industrial applications, have been extensively tested and demonstrated. The solution is robust and directly applicable.

Current methods for decreasing noise and vibration in machine-tool spindle bearings remain limited (notably, it is difficult to

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ensure temperature control across the entire speed range while eliminating noise problems). The Butterfly cage represents a true **universal** breakthrough, **without drawbacks**. It is compatible with all materials and requires no modification of the bearing or spindle assembly.

Thanks to a deep understanding of ball bearing kinematics, an innovative design approach, and proprietary computational modeling tools, the mechanisms that govern cage instability have been precisely identified and understood. This has been pivotal in the development of the Butterfly cage: a new, unique, unconditionally stable cage (patent pending).

For the first time, it is possible to explain what operators hear during rattling or squealing noise, or what appears in a frequency analysis. And for the first time, a **reliable solution** exists that has been implemented and fully tested up to the limits of the super precision bearing catalogs.

Returning to the tightrope walker analogy: a bearing equipped with the Butterfly cage no longer balances on a narrow rope of instability, it advances on a wide, secure highway of stability.



Fig. 3 - The Butterfly cage

5. How to overcome the Versatility and Speed challenge

The advent of the Cobweb bearing

What do we mean by Versatility and Speed challenge?

Versatility: the ability to adapt to a wide range of machining conditions, from light, high-speed operations to heavy-duty cutting, low speed operation.

Speed: the ability of the bearing to maintain stable and reliable performance not only at maximum speed, but also across the entire speed range. In other words, to be consistently effective at all operating speeds by counteracting the usual troubles: loss of rigidity, excessive rise in temperature, exaggerated variation in preload,...

Because today's milling and turning centers must cover an exceptionally broad variety of metal cutting tasks, spindle bearings are now required to function as true **multi-purpose** solutions. As a summary, modern machining equipments require high load capacity at low speed and a very stable behavior at high speed.

Currently, different bearing arrangements, contact angles, and ball materials must be selected to meet specific requirements. Alternatively, manufacturers often rely on so-called "**compromise bearings**", such as those with medium-sized balls for example.

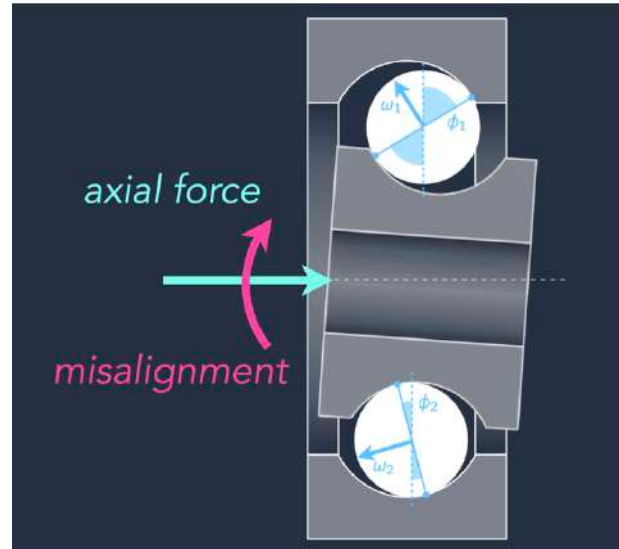


Fig. 4 – The effect of misalignment

However, one may ask whether it is possible to go beyond these compromise solutions and reach the performance levels of bearings specifically designed for either high speed or high load capacity, or even surpass them! Because in practice, load capacity comes at the expense of speed capability, and vice versa.

On Misalignment sensitivity

A common challenge in spindles is sensitivity to misalignment caused by the combination of axial and radial loads, as well as mounting error. More specifically, a well-known consequence in the machine-tool spindle and ball bearing industry is the **Ball Speed Variation (BSV) problem**.

The BSV phenomenon¹, characterized by non-constant ball velocity, can lead to cage failure, noise, vibration, excessive heat and,

¹ See our article: "On the Ball Speed Variation Phenomenon" available on the APO-GEE's website (www.apo-gee.tech)

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in the worst case scenario, bearing seizure. Current bearings designs provide only a partial solution. As a matter of fact, while high-speed bearings can support some moderate tilting of the rings, high load capacity bearings are not suited to deal with misalignment or significant combined loads. In other words, addressing BSV has always forced mechanical designers to accept a compromise.

The solution: the Cobweb bearing

After decades of having to accept inherent limitations, spindle engineers now have a

breakthrough solution: the **Cobweb bearing**, probably the most precise high-speed, high-precision bearing ever developed.

Originally designed to meet the extreme challenges of rocket engine turbo-pump bearings, where conditions include ultra-high speeds, combined loads, cryogenic environments, and difficult lubrication, the technology behind the Cobweb bearing can now be transferred to machine-tool spindles.

What sets the Cobweb bearing apart is its ability to go beyond compromise thanks to

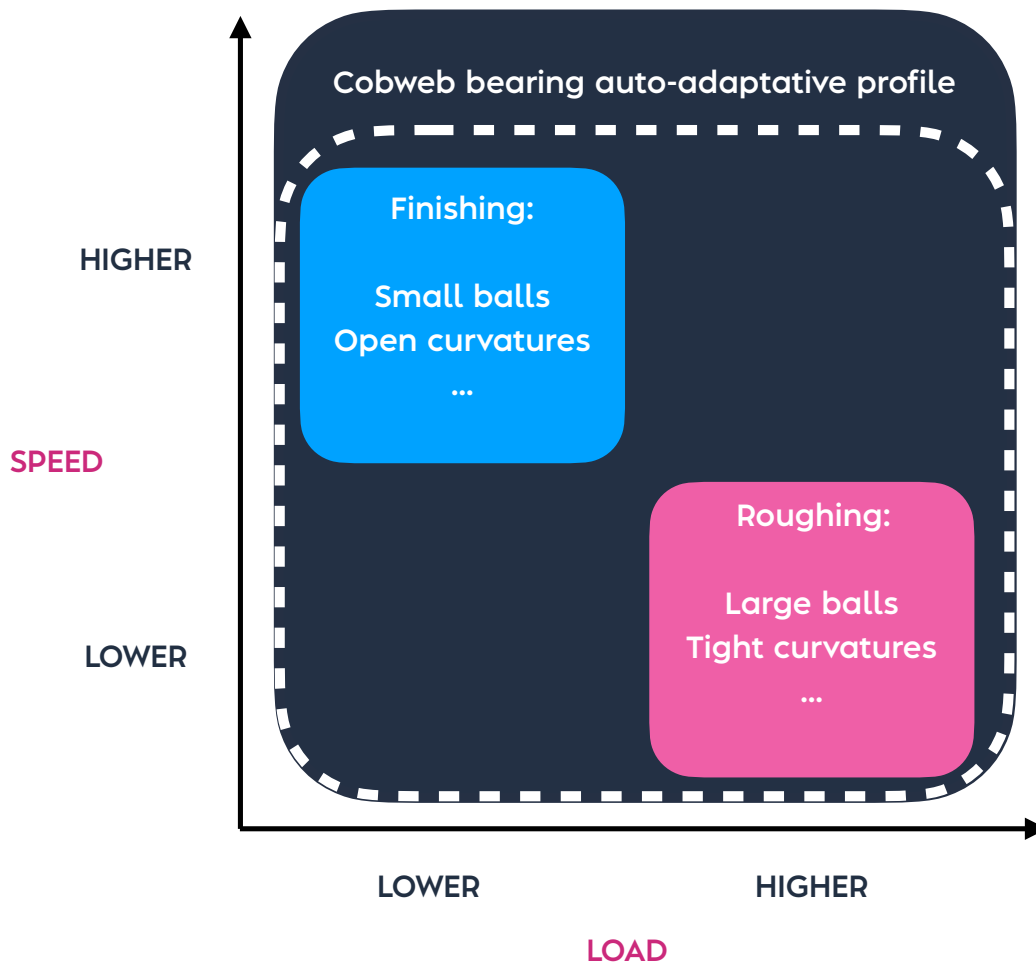


Fig. 5 - Beyond the compromise

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its unique **self-adaptive profile**. This design dramatically reduces the adverse effects of misalignment and Ball Speed Variation, promotes stable stiffness and preload over the whole speed range, while preserving load capacity. It can accommodate both axial and radial loads, from the lowest to the highest speeds.

No compromise on performance, no compromise on flexibility. Cobweb bearings can even be specifically designed to push performance further into the ultra-high-speed domain like never before.

6. Conclusion

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 the result of over 10 years of continuous and intense R&D, which has enabled the full computation of ball kinematics and a deep understanding of the mechanisms governing cage instability.

Driven by the necessity to overcome complex aerospace bearing challenges, this knowledge, combined with the development of new tools, makes it possible to envision entirely new standards

of performance in the demanding and fascinating world of precision machining.

The cage will remain the only free mechanical component in a spindle! Until now, it was uncontrolled, We can now master its behavior. Moreover, the innovative self-adaptive profile bearing makes it possible to solve what was long considered unattainable.

These breakthroughs not only enhance the performance of machine-tool spindles but also set a new standard for precision engineering.

If you are ready to explore **how these innovations can transform your applications**, we invite you to contact us and take the next step toward shaping the future of precision machining together. ♦



About APO-GEE

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

APO-GEE helps aerospace and defense companies 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 highly effective in other demanding industries such as in machine-tools, medical techs, and automotive.

Driven by innovation and intellectual property development, APO-GEE has introduced major breakthroughs in the bearing industry, including the Butterfly cage (an unconditionally stable cage), the Cobweb bearing (the smoothest high-speed bearing) and APO-GEE's unique computational tools.

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

www.apo-gee.tech