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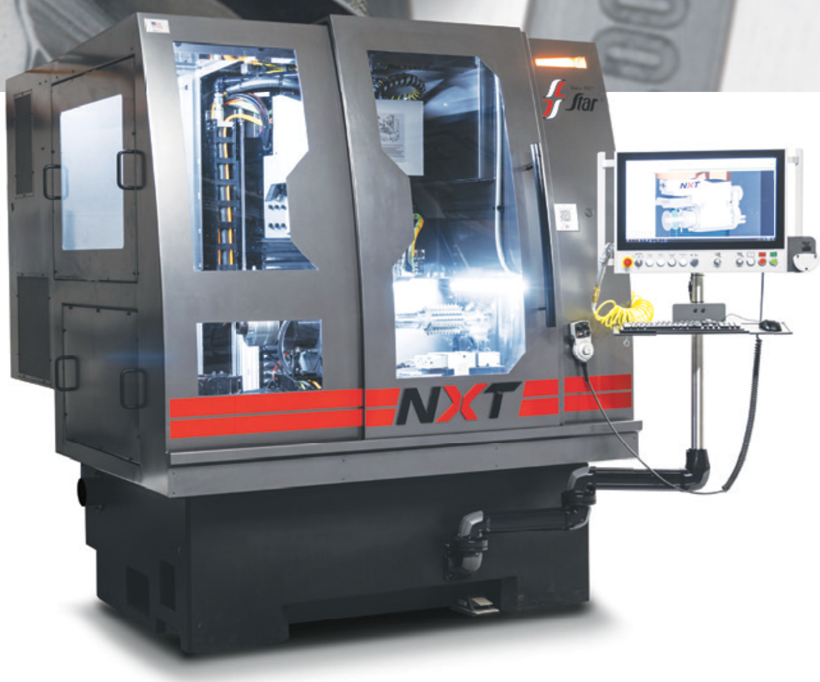

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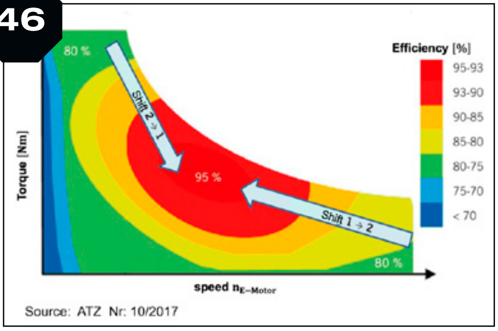

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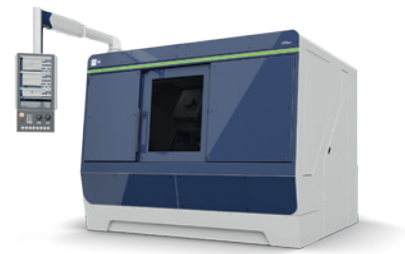

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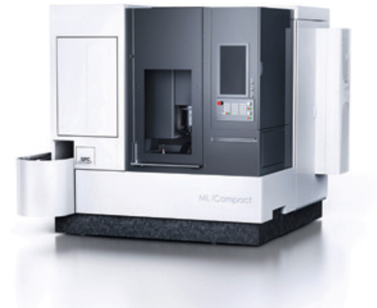

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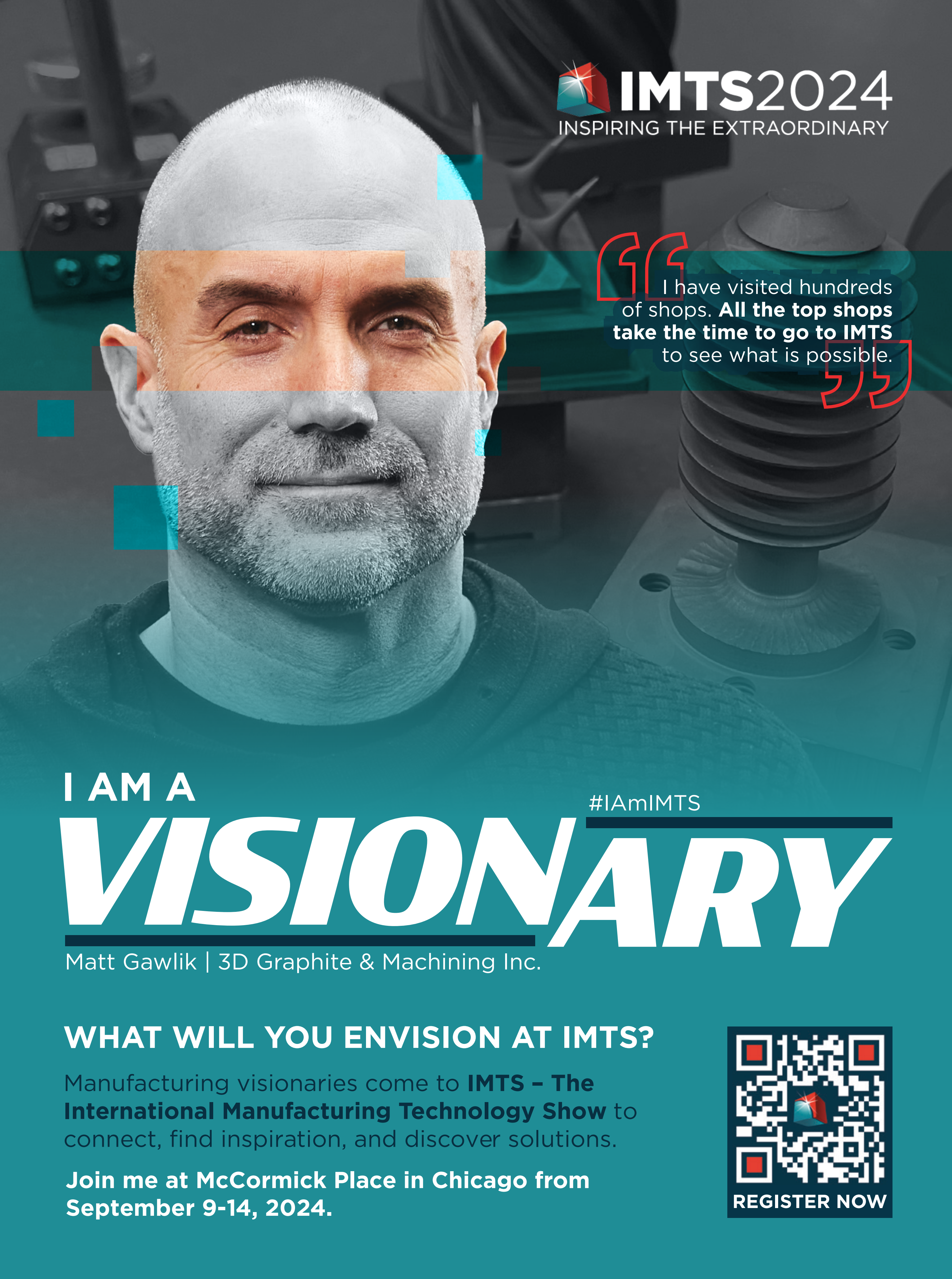
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GEAR TECHNOLOGY TV

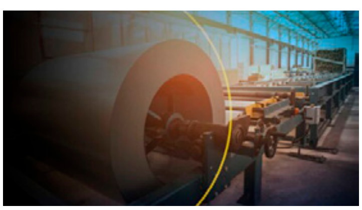
Manufacturing EV Gears

Gear Technology sat down with several expert machine tool suppliers to discuss the challenges of manufacturing gears for electric vehicles. The experts included Dr. Oliver Winkel of Liebherr, Pascal Diggelmann of Reishauer and Dr. Hermann Stadtfeld of Gleason. The discussion took place at MPT Expo 2023 in Detroit.

geartechnology.com/media/videos/play/272-ask-the-expert-manufacturing-ev-gears

EVENT SPOTLIGHT

AISTech 2024



With 100+ technical sessions and more than 300+ individual presentations, attendees can plan their day around the conference schedule and learn about the latest products and processes happening in every aspect of the steelmaking process. Sessions include safety/health, environmental technology, cokemaking, ironmaking, sheet rooling, metallurgy, MRO, lubrication, material handling and more. Join the premire steel industry event in Columbus, OH from May 6-9, 2024, at the Greater Columbus Convention Center.

geartechnology.com/events/5093-aistech-2024

AS SEEN IN *PTE*

Beckhoff Automation Provides Servo Drive Technology for Precision Machining

In Watch Valley, a region between Basel and Geneva, an ecosystem has developed over several centuries around the watch industry and the smallest precision components for micromechanical devices. Machine builders such as Esco SA in Les Geneveys-sur-Coffrane and Affolter Group SA in Malleray are an important part of this ecosystem. Their CNC machines are used to manufacture the smallest gears, screws, shafts, and other components at maximum precision, practically laying the foundation for the famous precision of Swiss watch movements.

powertransmission.com/articles/9723-beckhoff-automation-provides-servo-drive-technology-for-precision-machining

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Alexandria, VA 22314
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Which Half Are You In?

OK, audience. I'm going to divide you into two groups. Everybody whose company is a member of AGMA, please move over to the left-hand side of the room, and everybody else, please move over to the right.

According to our latest surveys, that should put about half of you on the left and half of you on the right. To those of you on the non-AGMA side of the room: Do you ever wonder what you're missing?

I've just returned from the AGMA/ABMA annual meeting in Napa, CA. Once per year, executives from the AGMA and ABMA gather to conduct the business of the association (see p. 52 for our follow-up article), but also to network, learn and have some fun.

This year's program included seven speakers, ranging from motivational to educational, and nearly everyone I've spoken to walked away with new insights on the economy, supply chains, the electrification of the automotive industry, artificial intelligence, the upcoming presidential election and innovative approaches to workforce challenges.

In addition, the annual meeting is always a great opportunity to meet with peers across the entire power transmission supply chain. It's just one of many association events where competitors, suppliers and colleagues can meet to advance the goals of the industry as a whole, conduct business, and—maybe most importantly—form lifelong friendships.

It makes me wonder why more of you don't consider crossing the aisle to the other side of the room.

I recently had a discussion with the founder of a gear-industry company who has been watching from the outside for more than 10 years and is just now beginning the process of joining AGMA. For 10 years he was intimidated and didn't know where to start.

But the AGMA is not like the high school cafeteria, where only the cool kids could sit at certain tables. In the gear industry, everyone's cool. Long gone are the days of clandestine meetings in smoke-filled back rooms. When our industry gets together, it's collegial, collaborative and inclusive. I've seen it up close and personal—not just at the annual meeting—but at every AGMA event I've attended.

Reach out to anyone who is involved with the association, and you'll see.

Of course, joining an association comes with a price tag, and that is always a consideration. For many companies, access to the latest standards and participation in the standards-making process is enough to justify the cost. But most people (even among the membership) don't know all the ways AGMA brings value to its members.

One example is the association's focus on the emerging technologies that will shape our industry for decades to come. See page 36 for our "Frontiers" column, written by AGMA's director of emerging technology, Mary Ellen Doran.

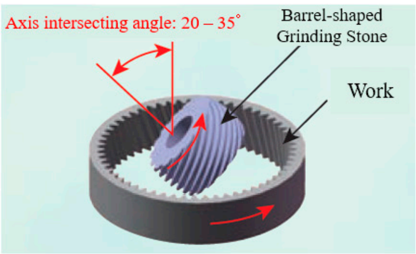
When you add in discounted educational opportunities, discounted exhibit space at MPT Expo and members-only events like the annual meeting, the value can add up quickly. There's not nearly enough space here to cover it all.

So if you're in the non-AGMA half of the room (or even if you're not!), I encourage you to visit *agma.org* to learn more. Or just reach out to me at *stott@agma.org*. I'll be happy to help you get involved.

Publisher & Editor-in-Chief
Randy Stott. Vice President Media

Nidec Machine Tool

DEVELOPS POLISH (GRINDING) METHOD TO PROCESS INTERNAL GEARS FOR MASS-PRODUCTION



Nidec Machine Tool Corporation recently developed a high-accuracy polishing (grinding) method to machine internal gears for mass production that are used for automobiles' drive units and transmissions and robots' joints. While there is already high-accuracy polish-machining methods for external gears for mass production, no such methods have been available for internal gears. After conducting research focused on this point, the company has achieved positive results in securing the level of accuracy and production that conventional grinding, honing, or skiving methods could not.

Though the planetary gear mechanism boasts such merits as high efficiency, high load capacity, and compactness, the gears used in the mechanism are required to be high-quality, as even a slight distortion in the gears as the mechanism's components affect the durability and transmission efficiency and may cause noise and vibration. As a growing number of products become electrified and automated, and as the need for high-precision gears increases accordingly, Nidec has realized this new machining method quickly and released it to contribute to improving gears' durability, transmission efficiency, and NVH (noise, vibration, and harshness) performance.

This latest R&D project identified and derived machining conditions based on Nidec Machine Tool's processing machines and technologies. This project is part of the joint research with Germany's RWTH Aachen University.

Processing machine: The company used ZI20A, the grinding machine that it used its unique technology and was launched in 2009 for internal gears for mass production. This machine can process internal gears with high precision to the degree of productivity required for mass production.

Selection of grinding stones for polishing: The company selected grinding stones, which are consumables, based on its preliminary assessment of their availability, economic efficiency, and suitability for autonomous driving.

Specifying machining conditions: By targeting Ra0.1µm and Rz1.0µm or less (a general surface roughness index for polish machining), the company derived high-efficiency machining conditions that would maintain the post-polish gear accuracy of ISO levels 3–5, while preventing grinding burn.

nidec.com

Kapp Niles

PROVIDES E-MOBILITY SOLUTIONS

For over 10 years, the mechanical engineering company Kapp Niles has been working intensively on the topic of gears in e-mobility and has established itself as a pioneer in this rapidly growing industry. With a focus on innovation and quality, Kapp Niles offers customized solutions to produce gearboxes and gears in electric vehicles.

Electric vehicles are the future of mobility. Kapp Niles is actively shaping this future with a dedicated team of highly qualified employees.

"We understand the specific challenges of e-mobility and work closely with our customers to fulfill their requirements and achieve first-class results with our machines and technologies," said Matthias Kapp, managing director at Kapp Niles.

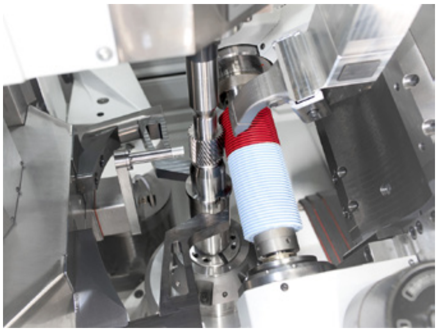
E-mobility requires different gearing solutions for different areas of application.

"Flexibility in the range of components is one of our strengths. We can fulfill a wide range of requirements here, from the fine machining of miniature gears in e-bikes and components for electrically powered cars to larger components in electric commercial vehicles," said Friedrich Wölfel, head of sales at Kapp Niles.

The drivetrain in electric vehicles must be optimized even more than in conventional vehicles with combustion engines in terms of efficiency and therefore range. A key component of the measures used for this is the optimization of the gear surfaces in the transmission. Fine or polishing grinding on Kapp Niles machines enables the highest surface accuracies to be produced economically and reproducibly.

"An ultra-fine surface with an increased material contact ratio can extend the efficiency of torque transmission and improve the range of electric vehicles. Our technologies offer customized solutions for this," said Patrick Duhre, team leader subcontracting at Kapp Niles.

In e-mobility, gearboxes not only have to be efficient, but also particularly quiet. Kapp Niles relies on intelligent process monitoring to identify noisy components during machining and reduce the return rate. This is an effective and cost-saving option and fulfils the high-quality requirements of e-mobility.



For the same reason, waviness analysis is becoming increasingly important for assessing the quality of gearing in electric drives. A software option for order analysis is directly integrated on the Kapp Niles measuring machines to enable quality testing for low-noise gears during series production.

"With our waviness analysis, we offer a precise and efficient way to determine the smallest geometric deviations as a result of preliminary process steps and to evaluate components using definable tolerance curves," said Dr. Philip Geilert, testing/fundamentals at Kapp Niles.

kapp-niles.com/en/e-mobilitaet

FVA–Workbench

VERSION 9 REDEFINES GEARBOX DESIGN

With the release of version 9, the *FVA-Workbench* once again sets new standards in gearbox design, enabling the seamless integration of the latest research results into industrial practice. As a groundbreaking interface between collective research and application, the *FVA-Workbench* accelerates development and innovation in drive technology. This new release is more powerful than ever, with innovative features for flexible load spectra and improvements in FEM components and shaft-hub connections.

New Features in *FVA-Workbench 9*

Flexibility in load spectrum calculations: individual power paths for each load stage

One new feature of *FVA-Workbench* 9 is flexible load spectrum calculations. In contrast to the previous method, in which the power was scaled across different load stages, this function makes it possible to define different operating states. Individual power paths and additional loads can be assigned to each operating state, particularly for consideration of auxiliary units. The time share, operating temperature, switching position, power flow data, and external loads can be freely selected for each load case. This data can easily be copied and pasted from Excel. A model snapshot can also be created for each load case, with detailed results that can be displayed in the overview tables in the report.

Efficient integration of gearbox housings: error prevention and faster workflows

The latest version of the *FVA-Workbench* includes new FEM features, especially regarding split FEM gearbox housings. Gearbox housings can now be imported as an assembly of individual CAD components and linked together. This not only helps to avoid errors when merging CAD components, but also saves time thanks to coarser meshing of less critical components. The housing components are shown individually in the Model Tree to minimize errors and simplify the overall process.

Detailed calculations for interference fits: elastic-plastic material models

In addition to several user-friendliness improvements, the stress hypotheses for tapered and cylindrical interference fits have also been expanded in *FVA-Workbench* 9. Calculations can now be performed according to the von Mises shape modification hypothesis in addition to the DIN 7190 shear stress hypothesis. This allows for the consideration of strain hardening curves to represent the material behavior more accurately during partial plastification.

More than just software—a bridge between research and industrial practice

The *FVA-Workbench* enables engineers to easily visualize complex relationships, simplifies the simulation and analysis of influencing factors, and automates processes. From conception to optimization—the software offers comprehensive approaches for all phases of gearbox development. The underlying calculation methods are based on the results of cutting-edge German research and are supported by the expertise of FVA members.

fva-service.de

Mitsubishi Electric

AUTOMATION PROVIDES MACHINE TENDING SOLUTION FOR TL AEROTEK

TL Aerotek, a small job milling shop customer, experienced a large influx of orders. To keep up with demand, they sought a solution that would alleviate labor uncertainty and help to grow the business. TL Aerotek turned to their long-time supplier of milling machines for support, Expand Machinery. Expand discovered an opportunity to automate the process of loading and unloading materials for the customer's machine tool, which already used a Mitsubishi Electric M8 Series CNC.

The solution, they hoped, would alleviate the need for manual, constant machine tending. Expand Machinery suggested using Mitsubishi Electric Automation's engineered solution, LoadMate Plus, to automate the machine tending process.

LoadMate Plus is a plug-and-play solution offering simplified robotic applications and is completely configurable, perfect for stand-alone cells, or to be integrated into a larger solution. For TL Aerotek, the 4x4 machine tending solution was connected to their existing machine tool and was equipped with an RV20, six-axis robot arm.

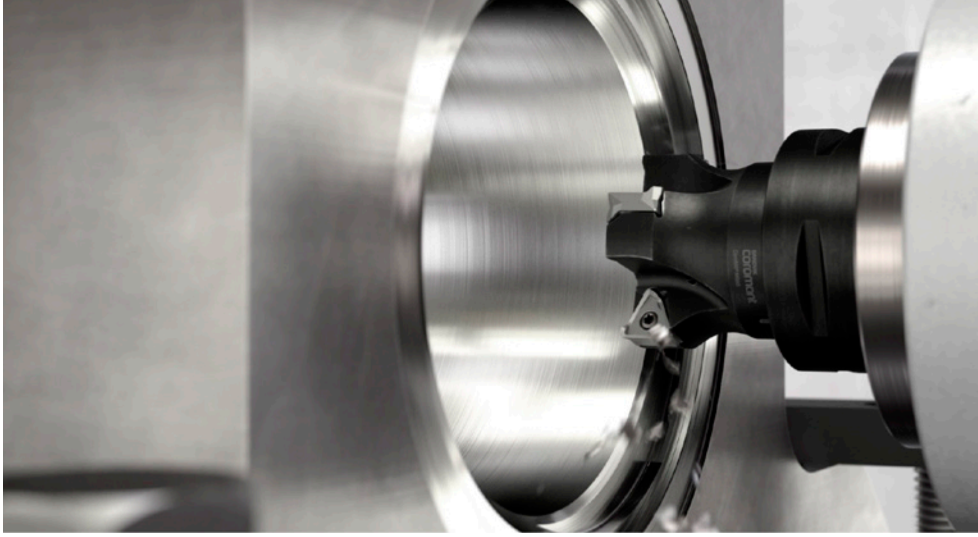
With a simple connection via Ethernet to integrate the LoadMate Plus with the CNC, the compatibility is built right in. After the integration of the solution, the system ran unattended for 24 hours, tripling the normal output that TL Aerotek had originally been experiencing.

"Both companies give me what I need: super support, performance, and reliability," said Tai Le, owner of TL Aerotek. "Because my machines are supported by Expand and Mitsubishi Electric, I know that if I do need help, I'll have it."

us.mitsubishielectric.com

Sandvik Coromant

INTRODUCES COROMILL MS60



Sandvik Coromant presents the latest addition to its family of milling tools: CoroMill MS60. The tool is tailored for 90-degree shoulder milling operations in steel and cast iron, but versatile enough to extend its competence across areas such as face milling and various ramping applications.

"CoroMill MS60 is a universal shoulder and face milling solution, primarily designed for roughing to semi-finishing operations in steel and cast iron, with two geometries capable of handling both these application areas as well as secondary areas ISO M and ISO S," says Jocelyn Lanaro, global product application specialist at Sandvik Coromant. "As such, it is possible to handle mixed material batches, including stainless steel and nickel-based alloys, without changing inserts."

As a robust multi-edge concept with positive cutting action, cutting forces are low for vibration-free machining, which translates into a high cost-efficiency per edge. Featuring a true 90-degree entering angle, CoroMill MS60 is mainly a shoulder milling tool—even though it excels in many other areas as well.

"From general milling operations to side milling, slot milling, helical ramping and face milling—CoroMill MS60 truly is an all-round solution," says Lanaro. "It is usually the first tool chosen during the early stages of universal milling operations, handling the roughing to semi-finishing stages, leaving the finishing to dedicated solutions."

Another standout feature to highlight is the direct pressed, six-edged inserts: "They are manufactured using a highly advanced multi-axis pressing technology, meaning it has been possible to gather both a smooth cut and ramping capability in the same insert, enhancing the versatility of the product."

Providing four different diameters in both metrics (50–100 mm) and inches (2–4 inch), CoroMill MS60 offers a compact yet comprehensive range, making both selection and usage easier.

sandvik.coromant.com

Gear Backlash in Robotics Applications

The search for flexibility, performance, and economical systems

Jacques Lemire, Principal, Lemire PBD Consulting

Recent headlines at technology conferences confirm that quantum computing with Artificial Intelligence (AI), biotechnology, nanotechnology, and robotics have the potential to reshape the world for the second quarter of the 21st century. This is certainly good news for gear manufacturers and allows them to be at the forefront of the technological history trajectory, as robots' joints and handling apparatus are made of motors, actuators, controllers, sensors, and gear drives. According to the International Federation of Robotics (Ref. 1), in 2023, the industrial robot market is expected to grow by 7 percent to more than 590,000 units worldwide. During the recent RoboBusiness Conference (Ref. 8) industry experts agreed that over the next 10–15 years, personal and collaborative robots (cobots) will exceed the industrial robot market and become common in homes, aiding with tasks such as cleaning, cooking, and caring for children or the elderly. These robots will be equipped with advanced artificial intelligence, allowing them to perform a wide range of tasks and provide personalized assistance to individuals. The annual production rate of 10 to 30 million robots per year is in the realm of possibility, and ramping up capacity to meet this exponential demand is a priority for US gear manufacturer leaders. Robert Kufner, president/CEO at Designatronics, mentioned, “At Designatronics, investing in automated high-performance machining centers and Industry 4.0 with the integration of intelligent digital technologies into manufacturing and industrial processes would be key to meet the future gear demand for robotics.” We also reached out to Denis Rancourt, professor in bio-mechanical engineering at Sherbrooke University in Quebec to learn more about future humanoid robots and exoskeletons and seek ideas for areas of potential improvement for gear drives. Dr. Rancourt revealed, “We elected to go direct drive on the majority of our bioengineering mechatronics projects because gearbox backlash, lost motion, and impedance introduce uncertainties and are difficult to model for accurate and safe motion control.”

Is the future of gear drives in robotics to grow exponentially or is it doomed because of the intrinsic problems with backlash, wear, unpredictability, size, and high cost? Over the past few months, we conducted research and interviews with leaders in the robotics and gear drive industry to understand the challenges and opportunities with robotics applications. We tried to understand how gear backlash problems could be overcome with better motion control, sensors, AI, and new drive technologies for robotics applications. This white paper does not provide a roadmap for overcoming backlash errors in motion control. Instead, it does examine gear drive backlash and the specific requirements of the robotics industry. It looks at current technology transformation and provides recommendations to the gear industry so they can gain a better understanding of current and future needs and have greater participation in the robotics market. This white paper hopes to generate a discussion, so the gear industry remains technically and commercially viable, and flexible in the future.

Background

Gear backlash refers to the clearance, or play, between the teeth of gears in a mechanical transmission system, as shown in Figure 1. Gear designers have strived to minimize gearing systems’ backlash due to the impact on precision, efficiency, noise, vibrations, wear, motion control, system complexity, and safety. Their significance varies depending on the applications, but designers need to carefully consider these factors when developing robotics systems to ensure they meet the desired performance and safety standards.

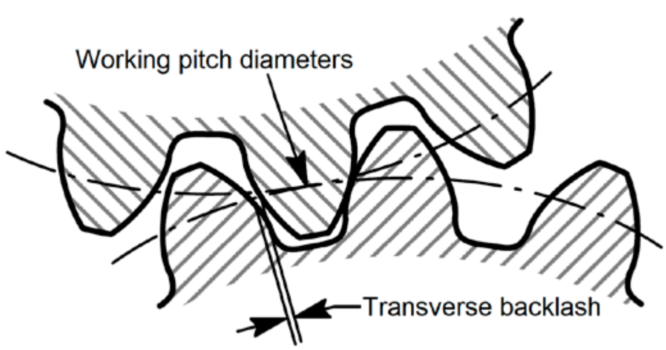


Figure 1—Gear backlash.

Precision and Accuracy

In high-precision applications such as industrial robots or CNC machines, minimizing gear backlash is crucial. Excessive backlash can lead to inaccuracies in positioning and reduced repeatability. This can result in poor performance in tasks that demand tight tolerances. Higher gearing ratio reduces the output position uncertainties, to the detriment of desired lower output mechanical impedance in certain applications.

Efficiency and Hysteresis

Torsional stiffness and backlash determine the surface contact area between the loading and unloading gears and correspond to the gearbox's efficiency. The phenomenon is called hysteresis. As a general term, hysteresis means a lag between input and output in a system upon a change in direction. Whenever these hysteresis curves are not available from the manufacturer, lost motion and stiffness variation can be used as alternative parameters to assess the hysteresis of the gearbox. Proper characterization of the hysteresis curves is critical for accuracy and results from the interaction of concentricity and other assembly errors with indexing errors, tooth corrections, stiffness variations during meshing, and other geometrical deviations. (Ref. 7)

Oscillations and Vibrations

Backlash can contribute to oscillations and vibrations in the robotic system, especially when the robot changes direction or stops and starts suddenly. These vibrations can affect the overall stability of the system and its ability to handle delicate tasks, as demonstrated in 2022 by Giovannitti (Ref. 2) in the *Journal of Intelligent Manufacturing 2022* and shown in Figure 2, below.

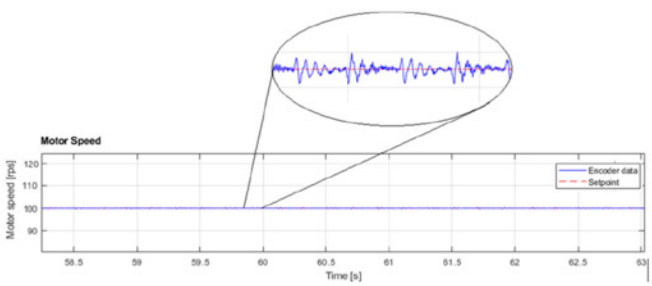


Figure 2—Noise and vibration due to gear backlash.

Wear and Tear

Over time, gear backlash can lead to increased wear and tear on the gear components, reducing the lifespan of the system and potentially leading to maintenance issues.

Control and Manufacturing Complexity

Compensation for backlash in control algorithms can be complex and may require additional sensors and software to account for the mechanical play. This adds to the complexity of the control system. In addition, the search for near-zero backlash increases design complexity and gearbox cost.

Position Control

Position control is a fundamental aspect of robotics, and it involves accurately and reliably controlling the position of robot joints or end-effectors. Backlash causes a discrepancy between where the load should be and where the load is actually located.

Position control is also crucial for various reasons. In many robotic applications, precise positioning is essential for the successful execution of tasks. This includes tasks such as pick-and-place operations, welding, assembly, and more. Poor position control can lead to errors in task execution. Typically, the control is done on the moving loads with a fixed mechanical and electrical characteristics system that uses an encoder on the motor shaft to provide the position and velocity information for control, as shown for closed-loop Proportional, Integral, and Derivative (PID) position control systems in Figure 3, where the errors come from the gearbox and associated backlash.

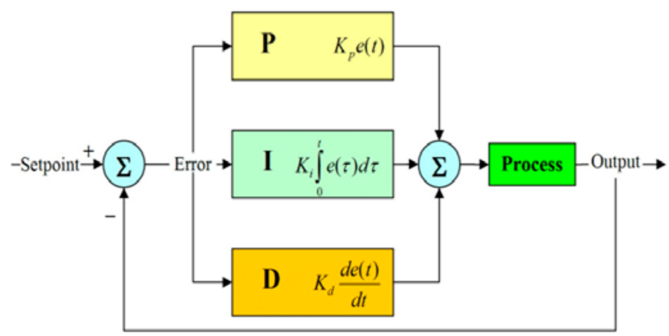


Figure 3—Basic PID control block diagram.

Depending on the direction of movement, the gear backlash may result in a different load position on the output side, causing delays and oscillations at the start or stop of the movement. The first solution that comes to mind is to mount a second encoder on the gear output shaft and base the control on a double feedback loop, increasing the

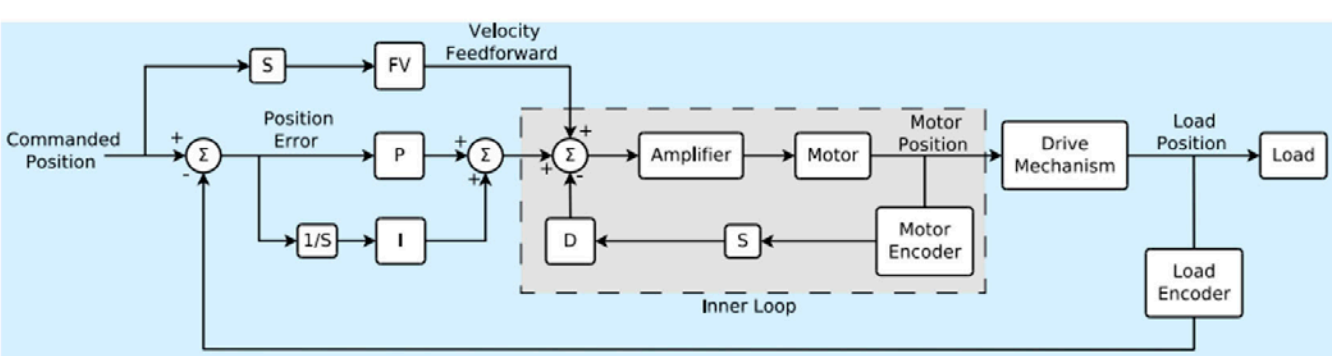


Figure 4—Standard dual Loop PID control block diagram (courtesy of Galil Motion Control).

complexity and error compensation. The controller first closes the inner loop, which is the velocity control loop, and then a second load position loop. See Figure 4 (Ref. 3). The velocity control loop receives feedback from the motor encoder, and this feedback determines the appropriate velocity feedback gain, which imparts a damping effect on the system to reduce oscillations.

Position errors can also be reduced with a higher gear ratio by increasing resolution and therefore minimizing the effect of gear backlash. The increased resolution is due to finer control of the system's output for a given input. With more teeth on the gears, the system can make smaller and more precise movements, resulting in improved resolution. This finer control helps minimize position errors. Lastly in a PID control system, higher gear ratios can enhance the overall rigidity of the mechanical system and improve the stability during position control, minimizing the impact of vibrations or external disturbances that could introduce errors.

Backdrivability for Safety and Human Interaction

Safety is a primary concern in robotics. Accurate position control ensures that the robot operates within its defined workspace and avoids collisions or accidents. Robots that work alongside humans require agile position control to ensure that they do not pose a safety risk to human operators. As such, backdrivability (i.e. low impedance system) is essential for mechanical compliance to be driven from the load side, managing contact with humans and undefined objects (Figure 5, ref 4). The backdrivability is characterized by its mechanical impedance consisting of the gearbox inertia, stiffness, and losses due to backlash and friction.

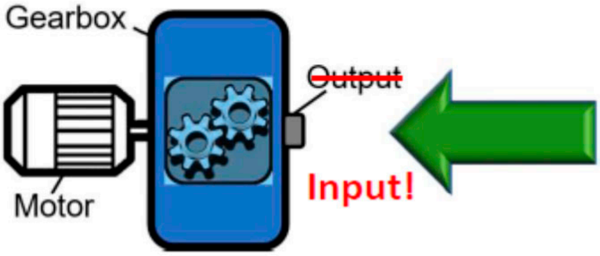


Figure 5—Backdrivability: Mechanical compliance from the input side.

Discussion

For most industrial robot applications, gearing backlash is an issue robot manufacturers have been able to work around by using strain wave gearing (also known as harmonic gearing), introduced in 1957, and later, cycloidal drive or cycloidal. Strain wave gearing uses a flexible spline with external teeth, which is deformed by a rotating elliptical plug to engage with the internal gear teeth of an outer spline, as shown in Figure 6. These drive systems provide compactness, relative light weight, high gear ratios, and high torque capacity.

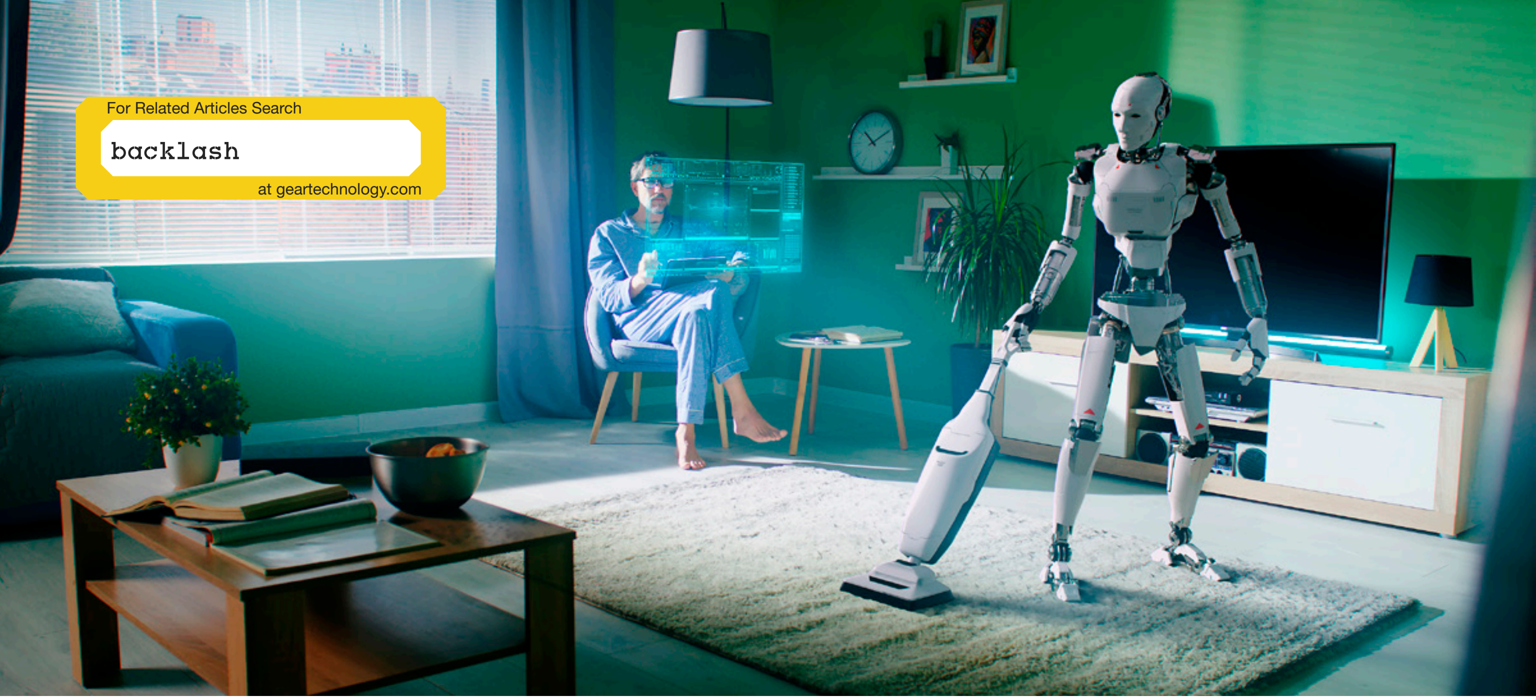

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Figure 8—Human-centered robots.

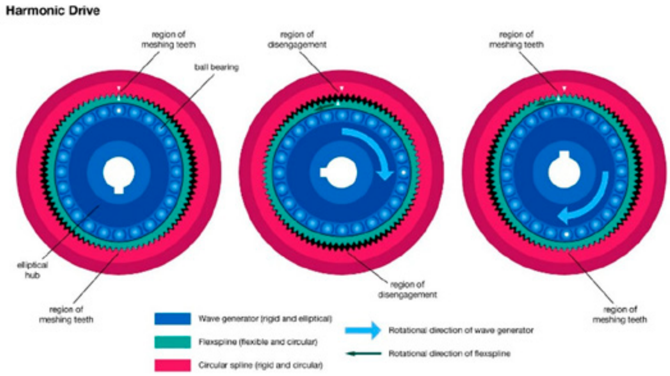

Figure 6—Strain wave gearing (harmonic drive).

John Tuohy (manager, business development at FANUC America) mentioned that FANUC, with their gear partner Nabtesco, has been able to produce robots with less than half of an arc-minute backlash under load and positioning precision of 0.02 mm at high velocity using large gear ratios ranging from 100:1 to 300:1. The challenge for gear manufacturers in the industrial robot market remains the predictability, limitation of material to minimize weight, size, inertia, and longevity of gear components.

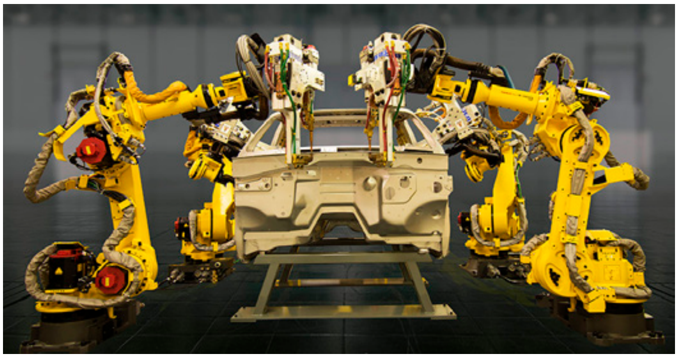

Figure 7—FANUC industrial robots.

The advent and the significant growth in the next 8–10 years of human-centered robots (humanoid and collaborative robots) has a significant impact on how the mechanical drive should be integrated. In conventional industrial robots, robustness and performance are linked to the robot's ability to maintain its position trajectory under an external disturbance force. In contrast, in human-centered robotics, the close interaction between robots and humans requires low forces when there is a deviation from the position trajectory. Therefore, they require low mechanical impedance or backdrivability for safety reasons, as discussed in the background section "Backdrivability for Safety and Human Interaction" above. In addition, human-centered robots are required to operate in an unpredictable environment with an undefined sequence of operations/tasks. The table below summarizes the differences in gear drive requirements and challenges for gear manufacturers for industrial and human-centered robots.

	Industrial robots	Human-centered robots
Gear General Requirements	• High torque density • High gear ratio • Controlled industrial environment • High speed and accuracy • High volume production • Deterministic system • Predictability, reliability, and maintainability • Position controlled • Minimal interaction with humans	• Low torque density and gear ratio • Backdrivability / low mechanical impedance • Position and force control • Flexibility in task performed in less deterministic AI controlled space • Interaction with human and multiple decision point • Unpredictable environment • Low noise and vibration • Multiple configuration and fragmented market • Position and force controller in proximity of humans
Gear Challenges	• Lower manufacturing cost • Material development for longevity and maintainability • Predictive reliability • Production capacity	• Lower weight and size • Backdrivability • Predictable backlash and hysteresis over product life and variable environment • Availability of data to accommodate environmental errors

We can see that gear backlash is one of the most important elements in robotics systems, but near-zero backlash may not be sufficient to meet the future need in human-centered robotics.

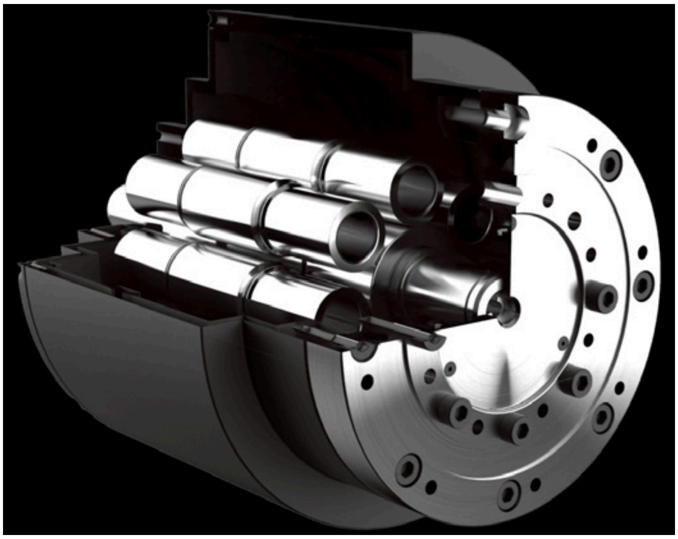

Figure 9—Compound planetary traction system inside the Archimedes drive.

New technologies, such as the Archimedes Drive from Innovative Mechatronics Systems with a Wolfrom drive and traction rollers (see Figure 9), are at the forefront of zero-backlash innovation. Thibaud Verschoor, founder at IM Systems, recognizes that true zero backlash is difficult. Engineers working on servo applications generally consider "zero backlash" to be between 0.5–5 arc min. (Ref. 6). Verschoor offers the following classification for backlash accuracy:

- Micro accuracy: < 1 arc-minute
- Increased accuracy: < 3 arc-minutes
- Standard accuracy: < 6 arc-minutes

The unpredictability of human-centered robots will require sophisticated integration of electromechanical hardware with artificial general intelligence to achieve the connection between a human's physical and cognitive behavior. Within the human environment AI database, the human-centered robot will evolve and learn from the information collected from the environment. These parameters, such as backlash, are needed to modify the motion control models from the initial build throughout its life, as components wear out and patterns and rules of operations change. As Robert James, vice president, product technology at Motus Labs mentioned, "The software will be driving the gear drive robotics joint. With AI, we will have to be able to predict drive degradation, feedback errors, and maintenance issues. The essence of the gear drive will be to understand the DNA of the gear profiles, its backlash, and its performance over time. We are the widget of the software industry." The drive backlash can no longer be considered an error in the system that will be compensated for, but instead, it should be integrated into the future human-centered robot blueprint.

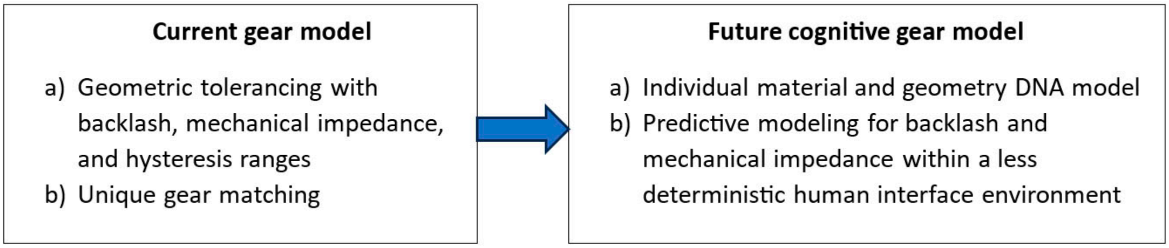

Figure 10—Proposed future cognitive gear model.

As human-centered robots become a motion-control computing problem, calculating errors from backlash range becomes the Achilles heel of drive systems. With computing power increasing drastically and the ability to collect large databases of data during gear manufacturing, the next generation of gears will have to go beyond backlash range to cognitive gear modeling. In this approach, the gear manufacturer and robot designer recognize that each gear is part of a more complex AI control system model, and each can be characterized with its own DNA, from the embryonic material science to the final manufacturing process and assembly. The proposed future cognitive gear model recognizes the backlash and mechanical impedance in the design and fabrication but also serves as an evolving function within the human-robot software model.

Conclusion

Despite recent progress in the range and accuracy of robot sensors and more powerful computing controllers, drive backlash remains one of the most significant problems in robotics. This is especially true for human-centered robots where gear ratios are generally lower than the industrial robots and backdrivability is required for safety. Gear backlash causes errors in the position and force control loop that affect the robot's mechanical impedance, generate noise, lose efficiency, and induce vibrations. From micro to standard accuracy gearboxes, the backlash value is sold with a zero to max range where the lower and upper limit might provide a significant difference in the motor/gear PID model. To further compound the issue, the backlash range changes over time due to wear in materials, lubricants, and environmental conditions. The environmental conditions and usage of human-centered robots are much more highly unpredictable than industrial robots. Backlash remains an unknown factor that the present robotics software can't insert into its motion-control model.

Today, robotics is a computer problem but "transmissions are where the problem starts" (Ref. 9) as Sangbae Kim, director of the Biomimetic Robotics Laboratory and a professor of mechanical engineering at MIT said. To play a major part in the next 10 years of human-centered robotics, the mechanical drive industry needs to develop a means to leverage next-generation computing power with a large AI database and capture gear digital mechanical DNA to allow computer modeling to account for errors in backlash and cognitive AI gears. These new gear drive digital models should be augmented by the research and development of new lighter anisotropic materials, a smaller drive envelope, and performance modeling in unpredictable environments.

The global robot market is expected to grow 50-fold in the near future. Increasing production capacity with the integration of intelligent digital technologies into manufacturing and industrial processes, such as IoT networks, AI, robotics, and automation will maximize operational returns and lower the cost of industrial robot's drives.

agma.org/event/backlash-and-the-future-of-robotic-applications/

Lemire.PBDConsulting@gmail.com

Contributors

Special thanks to the following contributors to this article (in alphabetical order):

Mary Ellen Doran, AGMA Director Emerging Technology

Pablo López Garcia, Robotics & Multibody Mechanics Group, Vrije Universiteit Brussel

Kel Guerin, Co-Founder, READY Robotics

David Harroun, Vice President, Helios Gear Products

Robert James, Vice President Product Technology, Motus Labs

Robert Kufner, President and CEO, Designatronics Inc.

Jason Lazar, Nabtesco

Tim Pirie, Chief Technology Officer, CGI Inc.

Denis Rancourt, Professor in Bio-Mechanical Engineering, Université de Sherbrooke

John Tuohy, Business Development Manager, FANUC America

Thibaud Verschoor, Co-founder and Head of Product, Innovative Mechatronics Systems B.V.

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Forging Ahead

Speedy delivery of high quality, open die forgings, seamless and contoured rolled rings, and complex forged parts is essential to the growing wind energy sector

Del Williams

Specialty forgers can manufacture custom, high-quality, seamless rolled rings in a variety of materials and finishes in as little as eight weeks. Open die forgings and seamless rolled rings are essential components in the wind energy sector, contributing to the overall reliability and efficiency of turbines, generator systems, and transmission and distribution equipment.

Forgings for component parts and seamless rolled rings have a greater lifespan than other products due to their strength and durability, and are less prone to cracking or warping, making the option ideal for critical components requiring high tensile strength. Depending on the metal and alloy, the rings are also resistant to thermal and chemical damage, which further extends longevity while reducing the need for maintenance, repair, and replacement.

For the wind power industry, obtaining large seamless rolled rings and turbine parts promptly remains a significant challenge, however. Currently, it may take many months to receive the forged components after placing an order. This delay can have a severe impact on the production and maintenance schedules of firms that depend on replacement parts.

The power and energy industry needs parts forgings, which are critical component parts for equipment such as gears, turbines, bearings, clutches, couplings, drives, flanges, valves, machines, and robotics.

Rings are typically provided with a rough surface finish, which necessitates the use of CNC machining to achieve the required level of smoothness. This poses a challenge for machine shops with a high workload, as allocating machine time for finishing inevitably leads to a decrease in production speed and an increase in costs, ultimately impacting the end-use cost or profitability.

Fortunately, wind energy product manufacturers can rely on forging specialists capable of producing a wide array of shapes and sizes of custom forged parts, seamless rolled rings, and contoured seamless rolled rings with the required surface finish in under two months. One example, All Metals & Forge Group, an ISO 9001:2015 and AS9100D manufacturer of custom and standard open die forged parts and seamless rolled rings can cost-effectively deliver these components with the required finish within 8–10 weeks.

The range of forged products includes rings, discs, hubs, blocks, shafts (including step shafts or with flanges), sleeves, gear blanks, cylinders, flats, hexes, rounds, plates, and custom shapes. Carbon steel, alloy steel, stainless steel, nickel, titanium, and aluminum are among the materials used for forging. These forgings meet rigorous industry specifications such as ASTM, AMS, AISI, ASME, Boeing, SAE, GE, DIN, ASME B 16.5, ASME B16.47, and API 6A.

When speed and quality are essential, the wind industry can reap the advantages of an accelerated process for obtaining flawless rolled rings.

The Benefits of Open Die Forging

One of the chief advantages of open die forging is the customization it offers in the seamless rolled ring manufacturing process.

According to Lewis Weiss, president of All Metals & Forge Group, open die forging is ideal for providing large, custom parts. "We can produce seamless rolled rings or contoured rolled rings up to 200 inches in outside diameter, and custom forgings up to 40 feet long or 80,000 lbs.," says Weiss. All Metals & Forge Group has been manufacturing and selling open die forgings and seamless rolled rings for more than 50 years.

While open die forging is typically associated with larger, simpler-shaped parts like bars or blanks, the process enables the creation of "custom-designed" metal components.

To optimize efficiency and reduce costs, rings and other parts can be produced for the wind power and energy industry as near-net-shaped forged parts with more refined surface finishes.

According to Weiss, open-die forging facilitates the production of seamless rolled rings to exact specifications with optimized mechanical properties and structural integrity. He notes that the rings can be produced in a variety of alloys, sizes, and shapes specific to the requirements.

The forging of the rings is also cost-effective since the process reduces material waste and manufacturing costs. Since the rings are constructed from a single metal piece using a specialized ring rolling machine, there is no need for welding or assembly, saving time and labor. The seamless rolled rings are also more structurally sound because they create a circular grain flow in the material, following the shape of the ring, which increases strength and integrity, creating a refined grain structure. This can enhance the material's fatigue resistance and overall performance, resulting in a stronger, more durable final product compared to other methods of ring making, such as cutting from plate.

Near Net Shape Parts with Finer Surface Finish

Typically, when seamless rolled rings are forged, they are often left in an unprocessed state with a rough surface measured at approximately 500 RMS. As a result, significant CNC machining time is required to achieve a smoother surface for the finished machined part. This poses a challenge for machine shops as the allocation of machine time for finishing these rough parts directly affects production efficiency and delivery time to the client.

To optimize efficiency and reduce costs, All Metals & Forge Group frequently provides near-net-shaped forged parts with more refined surface finishes.

"Typically, we provide a 250 RMS surface finish. We can even provide 125 RMS. We can also drill holes and do contour forgings as needed," says Weiss.

"Some forge shops only offer a raw unmachined part. We produce a rough machine part, saving machine shop time and equipment wear and tear since we have already taken off the first rough cuts off the ring or forged parts," he adds.

In addition, the company conducts ultrasonic testing at zero expense to the customer to guarantee the absence of internal cracks, pits, or voids. This instills the utmost confidence in the quality of the parts, according to Tim Grady, management consultant for All Metals & Forge Group.

"In many cases, All Metals & Forge Group can offer ultrasonically tested parts that are more affordable than raw forged rings," says Grady.

Streamlining Delivery

In today's market, the procurement of forged seamless rolled rings usually takes a considerable amount of time, from 20 weeks to as much as a year, as there are long lead times in receiving the necessary steel from mills.

"When replacement parts are required, a delay of a year or more is not acceptable," says Grady. "Even 20+ weeks is a serious issue."

To expedite the process for customers, All Metals & Forge Group has established strategic partnerships within the industry, enabling the company to deliver many custom forgings in a timeframe of eight to 10 weeks. Furthermore, to minimize any potential production downtime for machine shops, the company strives to provide accurate quotes within 48 hours.

Positioning for the Future

The need to acquire seamless rolled rings will only increase in industries like wind energy that require high-quality custom-forged components that can safely withstand extreme forces with minimal repair or replacement. In these cases, working with an expert forger who can expedite the process will convey a significant advantage.

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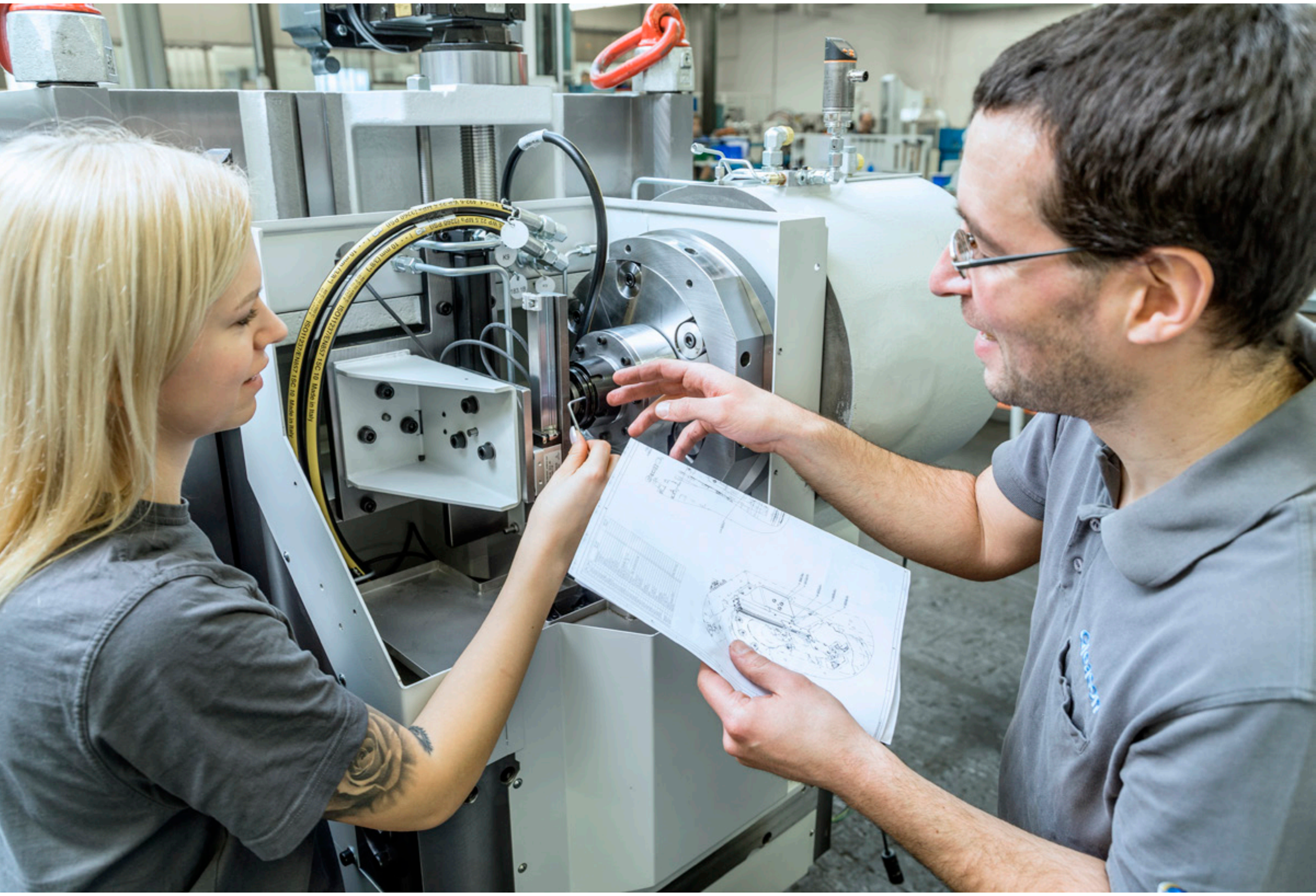
Specialty forgers, All Metals & Forge Group, can manufacture custom, high-quality, seamless rolled rings and other parts in a variety of materials and finishes in as little as eight weeks for the wind power and energy industry.

Training: Invest in Your Most Valuable Asset

New training programs and digital training technologies are closing the gap between shortages in skilled workers and an increasingly complex manufacturing environment. People are your most valuable asset, and investments in training pay enormous dividends downstream.

Robert Peyr, Director Product Management, Global Services & Workholding, Gleason Corporation



In addition to scheduling training events on important topics throughout the year, Gleason also offers individualized Training Courses, constructed to meet specific participant requirements.

By 2030, it's estimated that over 2 million manufacturing jobs in the US will be unfilled because of a lack of qualified talent. The CEOs of most manufacturers will tell you that their biggest challenge isn't machines or materials—it's manpower, and a global shortage of skilled workers. The gap between skilled technical positions and people with the training to fill them is perhaps at its widest since the dawn of the Industrial Revolution. Manufacturing technology, whether EV or AI, robots or cobots, is racing ahead at breakneck speed, and leaving older workers, and fewer, younger, and less skilled replacements behind.

Yet, for those manufacturers with the corporate cultures, work environments, and foresight to fully embrace training, there's never been a better time, or more tools, to take learning to the next level. These companies view training as an investment in their most important asset, skilled workers—and the benefits are significant:

- **More productivity:** Today's gear (and non-gear) production and inspection machines are designed to deliver exceptional productivity while relying less on the skills of the operator. Yet, the average machine operator or maintenance technician is today stretched thinner than ever. They must be more versatile than their predecessors, and able to manage a complex array of new technologies. With the right training, operators of these new technologies can help companies meet their ambitious production and quality objectives.
- **Improved quality:** Collaboration, and innovation, are byproducts of a strong learning environment. These workers are taught to strive for excellence and relish the challenges, and rewards, that come from high-quality efforts and outcomes.
- **Greater safety:** Today's manufacturing environments are highly complex. Operating both efficiently and safely in these demanding workplaces requires that everyone from machine operators to maintenance technicians understands what's at stake. Safety protocols, standards, and best practices can be deeply engrained in the workforce through training, thus helping avoid the cataclysmic costs of a safety-related accident.
- **Exceptional employees:** A company that nurtures learning as part of its culture has a decided advantage when hiring, training, and retaining skilled, highly motivated workers. These workers gain valuable skills faster and participate in a work environment that fosters greater satisfaction and a sense of accomplishment.

Train to Win

Traditionally, workers gained many of their technical skills over the years, whether in a technical trade school or apprenticeship and then on the job in close cooperation with older, more experienced tradesmen and technicians. This tried-and-true formula worked well when skilled labor was abundant, and a seemingly endless pipeline filled with eager applicants. Today, the Factories of the Future are, by design, much leaner, and the learning curve from novice to expert is considerably shorter. Nor are there nearly so many technical schools or skilled tradesmen to rely so heavily on.

As a result, training has quickly evolved in recognition of the new realities of the factory floor. The training tool kit has never been more diverse or effective. Training regimens today, at the best companies, are analogous to those of the most successful professional sports or Olympic teams. Instead of weight room, nutrition, and practice, workers use digital webinars, simulations, and classrooms. If modern training tools and techniques result in faster, higher, and stronger on the athletic field, they also produce faster, smarter, and better for companies seeking a competitive edge in the marketplace.

Knowledge Is Power

For Gleason, coupling training with technology, and sharing its deep know-how with all, has been a way of life almost since its inception in 1865. Who among the major automakers and their gear suppliers, for example, hasn't sent a gear design engineer to the Gleason Gear School over the years? Today, Gleason now offers what is considered the industry standard for the training of engineering, production, purchasing, and administration personnel at those companies that produce and consume gears. These training programs are flexible, digital, comprehensive, global, and, perhaps most importantly, affordable (even, in many cases, free of charge). Consider all that's now available to you:

E-Learning: Online Courses and Gear Trainer Webinars

E-Learning takes place—as the name suggests—on the computer desktop, and often in the form of webinars and streaming services. Online seminars can be organized practically on the fly and are being used more and more frequently in employee training to save time and travel costs. Content can be easily tailored to individual requirements. These also lay the groundwork for the more comprehensive training courses that take place downstream. A variation is the Gleason Gear Trainer Webinars Series, free of charge and produced once a month, which launched during the pandemic to keep customers connected when working from home. This highly successful series has grown from just a few viewers each month to many thousands today. Gear Trainer Webinars cover a variety of topics on bevel and cylindrical gear manufacturing technology, including gear and transmission design and simulation, soft cutting and hard finishing processes, metrology, tools, workholding, software, and Industry 4.0 production systems. The webinars include a mix of different media including demonstrations via live stream in a variety of languages. For 30 minutes, Gleason's training experts offer insight and analysis and answer any question raised in the following Q&A session. At gleason.com/training, a recording of past webinar topics is available for streaming, creating one of the most comprehensive knowledge databases in our industry, with topics related to all aspects of bevel gear and cylindrical gear manufacturing. It's all free of charge for customers with a myGleason account.

Virtual Online Product Training

For product-related training on all aspects of a Gleason machine, Gleason offers virtual courses, created exclusively for the respective companies and their new Gleason technologies. Digital simulations help to familiarize participants with certain techniques and processes using a host of training scenarios. Additionally, cameras capture action and demonstrations live to enhance effectiveness. Gleason also enables users to gain access to the connected cloud as a Gleason Connect+ option, opening the possibilities of remote communication and a live, visual connection between the customer and Gleason.

KISSsoft Training: Design and Simulation

Based on the current KISSsoft software release, users can learn more about these universally popular, and powerful, gear design software tools through training courses focused on module-specific topics and the latest trends in gear manufacturing tech-

Gleason offers virtual courses, with digital simulations to support a multitude of training scenarios.

Based on the current KISSsoft software release, users can learn more about these powerful gear design software tools through training courses focused on module-specific topics.

nology. These courses have fixed dates and are conducted either at KISSsoft facilities or via live streaming. Registration can be done through the KISSsoft or Gleason website. Customer-Specific Training Courses are available. KISSsoft webinars are also very effective, and web demos inform about various subjects in the calculation programs KISSsoft and KISSsys. In the USA, additional KISSsoft training courses are offered with fixed dates at the training center in Rochester, NY, with targeted programs tailored to US customer needs.

Training Events: Targeted to Important Technologies

Training events on important topics with widespread interest take place on fixed dates throughout the year. They are conducted either at Gleason plants, offices, or at an independent site that's well-suited for training. On the training website, it is possible to filter for topics of interest and the closest training location to find the best fit for a specific training need. If scheduled pieces of training do not contain the topic or location that is desired, Gleason offers individualized training courses, constructed to meet specific requirements. Throughout 2024, Gleason is offering over 100 courses online and ready to book.

Gleason Gear School: Basic Gearing Technology Seminars

Seventy years after its inception, the Gleason Gear School remains an important program in the gear industry. Training classes are available both in-person and online and provide fundamental gear technology training with a focus on cylindrical gears. Today, the "Gear School on the Road" series features a mobile and more compact version of Gleason's traditional Gear School to cater to participants who cannot travel to one of Gleason's global operations. Additionally, the Virtual Gear School is provided via live stream to participant's offices and home offices and is the perfect alternative to in-person training in one of Gleason's operations. All Gear School formats are intended for anyone interested in learning more about the world of cylindrical gears. Courses are regularly attended by participants who work in the gear design and manufacturing industry, including engineering, production, purchasing, and administration.

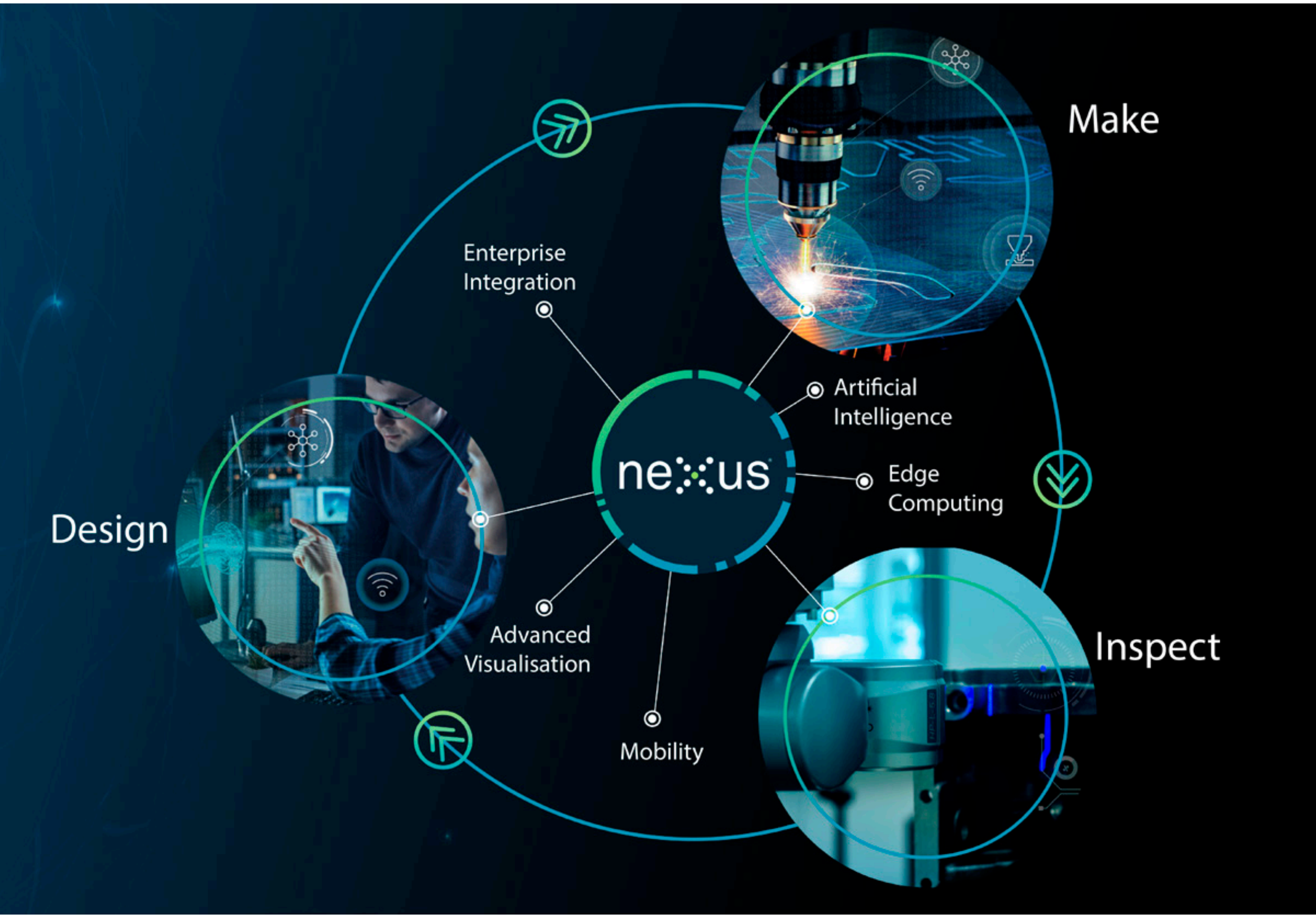
gleason.com/training

The "Gear School on the Road" series features a mobile, compact version of Gleason's traditional Gear School, for participants who can't travel to a Gleason global operation.

Delivering on the Promises of Digital Twins and Big Data

Balancing accuracy and precision in ISO 6336

Barry James, Senior Technical Leader, Hexagon Manufacturing Intelligence



As a community, we gear engineers collaborate and share ideas to progress our collective capability. Technology progresses based on our efforts, and we have seen solid advances in the performance of our products as they become quieter, cheaper, more efficient, and more power dense. The pages of this magazine (past and present editions) are filled with examples where talented engineers have dug deeper into a subject using a more precise approach to a particular area concerning gear performance. The implied belief is always that greater precision (complexity) in the calculations brings greater accuracy (alignment with reality).

Of all the performance characteristics of gears, durability/reliability is the most important. No matter how quiet, cheap, or efficient a machine is, it counts for nothing if operation fails. ISO 6336 delivers the standard for how to design gears, so one might assume that every gear engineer universally has a firm grasp of how to target a specific level of reliability—how to achieve the specific trade-off between over-design (excess size, weight, cost) and under-design (excess failures)—along with a statement on what is the anticipated failure rate for a given design. However, this turns out not to be the case.

A safety factor of 1.0 indicates 1 percent of the population will fail. However, if a different safety factor (say 1.2) is achieved, no information is given by ISO 6336 about the failure rate. A range of different research papers exist that explore the variability of gear failures, converting this data into numbers suitable for prediction through simulation, and these were summarized in a Gear Solutions article a few years ago (Ref. 1). Surely this provides the answers.

Unfortunately, the different sources suggest data that give wildly varying outcomes in predicted reliability (Ref. 2). The spread of results is not trivial. Take the safety factor of 1.2. Depending on which reference values for reliability you take, the predicted failure rate may be either 0.38 percent or $3x10^{-14}$ percent, (Ref. 3) i.e., from "reasonably frequent" to "vanishingly improbable even if applied to all the machines mankind has ever made"! It is almost as though you can "decide what result you want, and you will find a paper to give you that result."

This is not to say that gear designers are clueless or negligent. In practice, each company has values in target safety factor/stress that have been developed and refined over the years based on experience and 'not getting into trouble', to be handed down to the next generation. However, this is still a long way from really being able to carry out a quantifiable trade-off between gear center distance (or any other design parameter) and failure rate. Hands up—which gear engineer wants to admit to their client or their boss that they do not really have any idea how many failures will occur for the gears that have just been designed? This is not how it is supposed to be.

So, despite all the efforts of gear researchers over the decades, there is surprisingly little agreement on how to predict what is the most important performance characteristic during design.

What is more is that this is reflected in another group of engineers with an interest in gear reliability—the maintenance profession. For any expensive or safety-critical asset, knowing how long to run a machine, when to maintain it, and when to shut it down, is vitally important. Maintain too often and large

	Safety Factor			
Standard Deviation as % of Mean	1.0	1.1	1.2	1.3
3	1	1.3e-5	3e-14	-
8	1	0.057	2.8e-3	1.47e-4
13	1	0.24	0.064	0.018
18	1	0.43	0.21	0.1
23	1	0.6	0.38	0.26

Table 1—Percentage failure rates at different safety factors depending on which reference data you take for the variability of gear material strength.

costs are guaranteed, too infrequently and failure may occur, risking even higher costs and safety problems.

Practices such as Reliability Centered Maintenance (RCM) were developed to balance risks and optimize maintenance schedules, using a data-driven approach. So, what do RCM practitioners say about gears? Yet again, we see a variation in the recommended data for gear reliability (Ref. 4) that extends even wider than that from the design analysis research papers. Again, you can pretty much make up whatever result you like, and you can find data to give you that result. The situation is no better for our close cousins in the world of rolling element bearings. Here, the judgment is clear—major organizations such as NASA (Ref. 5) and the principal reference book for RCM (Ref. 6) written by one of its founders (Ref. 7) have decreed that bearings fail at random.

So, it is a salutary thought that, despite all our efforts to characterize the behavior of gears, designers do not really know what their failure rate will be, and those who maintain the machines that contain gears think they fail at random.

Some have suggested that this will change. "Big Data" and "machine learning" are on their way to rescue us! Everything will be monitored, observed, and correlated. "In the future, there will be no need for physics-based simulations, as everything will be a regression algorithm," was how one leading engineer put it at a conference (Ref. 8).

This approach has profound problems. Firstly, without a physics-based framework, all data, on every machine, needs to be recorded and stored forever—you can never know which snippet of data is irrelevant and which will hold the key to insight. A few short minutes of rough calculations indicate that this would lead to absurd quantities of data being retained that would incur vast costs and, incidentally, lead to huge energy bills and environmental damage.

The second problem has been highlighted by the RCM community for over 45 years, which is that catastrophic failures tend to be very rare, meaning that there is little or no data from which failure models can be derived—take helicopter gearbox failures as an example. This is what is known as Resnikoff's conundrum (Ref. 9).

Hexagon takes a different approach. Essentially, it is not physics *or* data, but physics *and* data—combining the established physics-based framework with the opportunities that Big Data and big processing capability bring. Big Data has its role to play in providing hitherto unprecedented quantities of data, but it needs to be interpreted within the framework of existing methods such as ISO 6336.

It is all very good to describe grand ideas with a broad brush, but the devil is in the detail and the proof that it works relies on demonstrating an implementation that delivers value. This has been the focus of Hexagon's work over recent years with a number of globally renowned vehicle manufacturers.

The starting point is the vehicle usage data. Every vehicle gearbox is designed according to a duty cycle, which is intended to represent the usage that the gearbox will experience in operation. It may be accelerated/condensed (for the purposes of rig testing), but it is supposed to represent in-service usage regarding fatigue damage and reliability.

The problem is that, out of a fleet of nominally identical vehicles, each one will be driven differently. Small-scale studies have taken place to try to quantify this over the decades (Refs. 10, 11), but this has done nothing more than to scratch the surface of the issue and it has remained far too expensive to install telemetry equipment such as strain-gauged driveshafts on more than a handful of vehicles.

The situation regarding vehicle data is now changing. The development of connected and autonomous vehicles (CAVs) means that vehicle connectivity has reached levels not previously seen and large quantities of valuable data is available. For each company and each vehicle this varies, however, in general, it means that signals from the CAN (Controlled Area Network) bus are available, including the torque and speed of the prime mover (the internal combustion engine or electric machine, as appropriate) and the selected ratio (if appropriate). Depending on the company, this can be collected on the vehicle and uploaded to the Cloud, whether this is periodically, daily, or more frequently (Ref. 12). Essentially, the driving profile of every individual vehicle can be known.

This provides the opportunity for a digital twin of the gearbox. Alongside Big Data and the Internet of Things (IoT), a *digital twin* is another phrase that is widely used, often misused, promises much, and usually under-delivers. What does it mean within this context?

Hexagon's recent work (Refs. 2, 3) goes into the details of the origins of the term *digital twin* (Ref. 13) and the basis on which Hexagon uses the term in relation to others. In summary, the Hexagon digital twin is where the digital asset shadows the physical asset (the machine) during its in-service operation, extracting operational data and, potentially, feeding this back to the machine for performance optimization.

This is separate from a *design twin*, which is essentially a computer-aided engineering (CAE) model. However, there is a close relationship between a CAE model and an in-service digital twin. In the case of gearboxes, the digital twin was based on Hexagon's Romax software, which has been used worldwide for gearbox design since its release in 1994. Meanwhile, data handling, processing, queuing, results plotting, etc. was handled by the various capabilities of Nexus, Hexagon's open digital reality platform for manufacturing that is developed to provide connectivity and interoperability across all aspects of design, manufacturing, metrology, and in-service operation for all Hexagon's client industries.

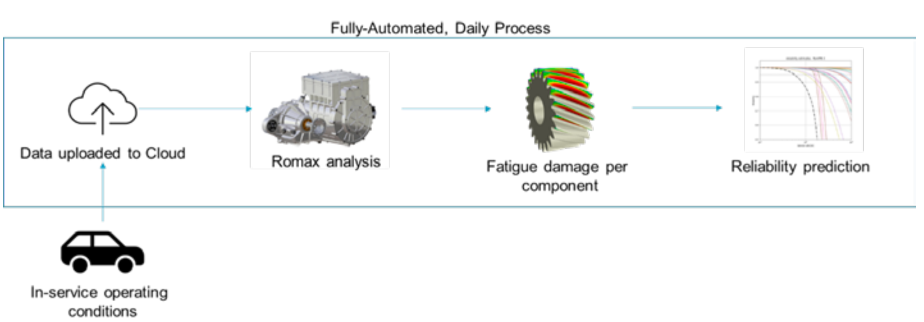


Figure 1—Overall workflow for Hexagon's gearbox digital twin.

The work saw vehicle operational data uploaded to the Cloud where the Romax Digital Twin calculates fatigue damage and then predicts reliability for the gears and bearings. The reliability methods used were based on recommendations from the standards in the case of bearings and Hexagon's best judgment from the literature search. Detailed explanation and justification of this is covered in Hexagon's papers at 2023's VDI International Gear Conference (Ref. 3) and AGMA Fall Technical Meeting (Ref. 2).

One insight has been apparent from the start, which is the extent to which vehicle usage varies across the fleet and therefore affects gearbox fatigue. Of course, this makes sense qualitatively—everyone knows that some vehicles are driven hard, some gently, and this will influence gear failure rates—but acquiring the data meant that this impact could be quantified.

What this showed (Ref. 14) is that the variation in vehicle usage is so great that carrying out failure analysis purely based on vehicle mileage/hours of usage is so grossly inaccurate as to be meaningless. Even if the simulation model of the gearbox is perfect and the components behave with great consistency, omitting the variation of vehicle usage from the input data injects such enormous variability into fatigue damage that the results are nonsense. It is simply a case of "garbage in, garbage out."

In many respects, this explains the broad range of reliability data proposed by the research papers and used by RCM professionals, and the reliance by gear designers on experience-based values for safety factor. Since it has not previously been possible to know the usage data for each vehicle, failure analyses have been based on mileage/hours and components have appeared to fail (approximately) randomly, when this may well not have been the case had suitable data been available.

Hexagon's work is a process of identifying these key sources of "garbage" that cause this randomization and filtering them out, converting "unknowns" into "knowns," which can be quantified in the analysis. Rome was not built in a day and not all of these have been covered to date—the process is slow and steady and each time a new factor is incorporated into the analysis checks must be made to ensure that the results make sense. Nonetheless, sufficient work has been carried out to show that, within Hexagon's wider portfolio, it can account for variations in gear manufacturing (Ref. 15) and road-induced shock loads in its further work.

Thus, there is the potential to deliver unprecedented accuracy in the prediction of gear (and bearing) failures. The intention is to use this to recommend service intervals or maintenance inspections based on vehicle usage.

The description to this point assumes that the prediction of component reliability is perfect and all that is needed is accurate input data on vehicle usage, gear manufacturing, and shock loads. However, this may well not be sufficient. Most companies only have a vague estimation as to the fatigue strength of their gear materials, and it is highly likely, for example, that the data selected by the gear designer does not match the material's real performance. Frequently it is observed that Romax users automatically plump for "Medium Grade Case Carburized Steel" regardless of the actual composition of their material, its cleanliness, the capability of their heat treatment process, or their grit blasting/shot blasting/shot peening processes.

This is where the next phase of the digital twin work comes in. For each vehicle in the fleet, the usage data will be known. Not many of them will see their gearboxes fail but out of a fleet of many thousands, some will. Understanding these failures on a case-by-case basis will be assisted by being able to inspect the usage data to see if the vehicle was driven aggressively/unusually compared to the design assumptions. However, the key value comes from aggregating the failure data across the fleet.

Meeker and Escobar (Ref. 16) have illustrated "sample size analysis," whereby the confidence in a result relates to the number of samples being tested plus how far along the test regime they have lasted. Since we have a very large sample size, we can derive insight with great confidence even when there are just a few failures.

Adoption of the digital twin across a fleet of vehicles will provide sample sizes and confidence that will dwarf the approaches used to date to understand reliability. Often companies sign off on a gearbox design by rig testing a sample of prototype gearboxes prior to the start of production. This sample is small—somewhere around 5, perhaps a few more. Analysis shows (Ref. 17) that this actually provides very little confidence in the result. Even university research programs, on which the S-N curves of gear materials are based, extend to a couple of hundred samples, although FZG can point to a dataset of around 1,000 pitting and 1,700 bending test results for the common case hardening steels 16/20MnCr5 or 18CrNiMo7-6 (Ref. 18). This is all very good if you use one of these steels, but Hexagon has still seen large variations in results for 20MnCr5, for example, owing to variability of heat treatment and shot peening, factors which are defined by each manufacturer. By comparison, vehicle manufacturing companies could build up sample sizes running into the hundreds of thousands or even millions of gears.

This is not to say that rig testing before the start of production should be stopped, but rather that the processing of vehicle usage data and component failure data, combined across a sizeable fleet of vehicles/machines, could provide unprecedented accuracy in the ability to predict component fatigue and reliability.

How would this all actually work? Recently (Ref. 17), Hexagon carefully stepped through the process for how a digital twin could automatically adjust the calculation such that the predicted failure rate matched the observed failure rate. This would not involve throwing away ISO 6336, or appending additional complexity to its calculation, but simply adjusting parameters such as application factor, allowable stress, and Weibull shape parameter. Note the change in emphasis from precision (adding complexity) to accuracy (making sure the predictions match the observation).

Basing the method on ISO 6336 has another key advantage, which is that it uses the language that existing gear engineers understand. The leading experts in each manufacturer will have learned their trade using this approach and have had at least 2 decades of experience in its application. This approach builds on that experience and tweaks the input values, providing evidence to justify such changes.

The current limitations of ISO 6336 described apply to all implementations of the standards in all codes. ISO 6336 permits companies to adjust values for gear material fatigue strength and application factor. What we show here is that it is now possible to get a clear indication of these values. The answer is not to throw away ISO 6336 (as some advocates of Big Data suggest (Ref. 8) or add further layers of complexity (precision) to the calculation, but to develop an approach that uses each company's data to derive the correct input values to make their ISO calculation accurate. Prioritize accuracy over precision.

In summary, there exists the possibility to deliver on the grand promises of Big Data, digital twins, IoT, etc., promises that are too often spoken about in revolutionary, utopian terms, but which usually fail to deliver. By taking a pragmatic approach and taking advantage of recent advances to convert important input data (vehicle loading, manufacturing accuracy, shock loads) from assumed to confirmed values, Hexagon is working with its clients to deliver these promises.

Behind all the gear engineering and maths is *Nexus*, the framework that coordinates all the data and makes the implementation of the digital twin possible. Hexagon's roadmap sees *Nexus* taking a significant role in the development of digital twins, extending from vehicle gearboxes to other fleets of geared machines such as wind turbines, then other fatiguing components and other physics that Hexagon covers (noise, heat, etc.).

Despite failing to live up to expectations so far, digital twins can and will deliver, as current projects are demonstrating.

nexus.hexagon.com

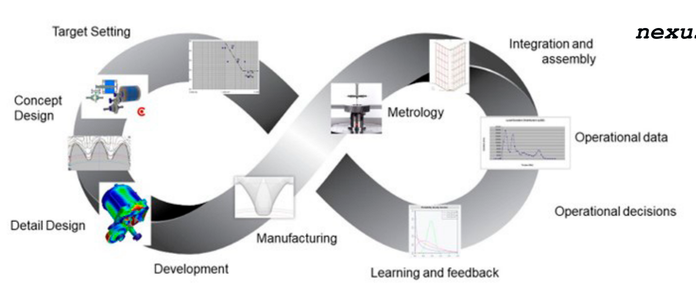


Figure 2—Completed digital thread covering the life cycle of gears.

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Footnote: For those perhaps not so familiar with the English language and the nuances of different definitions, it is perhaps necessary to emphasize the difference between *accuracy* and *precision*. If two shots are close to the bullseye but far apart from each other they are *accurate* but not precise. If two shots are tightly grouped but away from the bullseye, they are *precise* but not accurate. If both shots are close to the bullseye and tightly grouped, they are *accurate* and *precise*.

Unveiling the AI Revolution: Advancements, Threats, Opportunities

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Mary Ellen Doran, AGMA Director, Emerging Technology

Artificial Intelligence (AI) has gotten a lot of buzz lately, and rightly so—as James McQuiggan put it in our December emerging tech webinar, "I've never seen a technology advance and change so much in one year than I have with AI." While AI is not new, recent advancements in computing power have allowed developers to unleash very powerful AI tools to the public. Our IIoT Committee is exploring how this technology is being utilized in manufacturing in everything from task automation, predictive maintenance, and fraud detection to chatbots and other customer service-style tools. We hope you join us in these discussions.

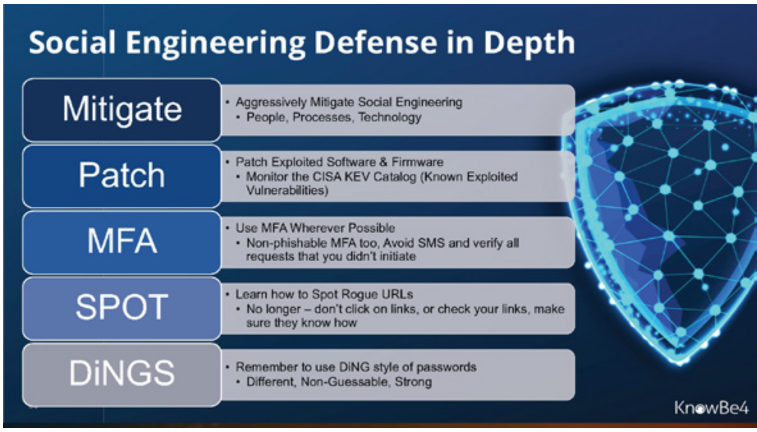
While most will use these tools for average work, there is already an increased threat as this technology aids those with more nefarious intentions. AI helps generate things quickly and is being used to generate phishing emails and attack programs. Again, James cites in his webinar that from 2022 to 2023 malicious phishing messages increased by 1,265 percent. On average, 31,000 phishing attacks are sent daily, and there has been a 967 percent increase in credential phishing. This just makes it ever more important to have policies in place to train your staff to watch for these threats. And it is not just learning to spot bad emails. There are examples of AI being used in voice generation to have accounting departments transfer money for what they think is an executive. Awareness is crucial. Always take a breath when getting a message that is outside the normal practice of business and double-check sources.

The committee will be following NIST's Artificial Intelligence Risk Management Framework and the development of the AI Security Center at the National Security Agency. We hope to bring in presenters, like James, to continue the discussions this year to keep you aware of the constant changes in this space. If you have not watched his webinar, it is on-demand on the AGMA website: *agma.org/event/ai-steered-safety-geared-ais-voyage-with-gear-manufacturing*

In the AGMA Robotics Committee, we are having a similar conversation about the pace of technology. The topic is humanoid robots. As recent as July of last year committee members were hoping to see advanced developments of these new types of robots in three to five years. But in our meeting in early March, just days ago, many committee members commented on the number of developments that have been in the news in recent weeks. A video shows Tesla's Optimus moving at speeds 30 percent faster than previously shown last year and with more agility. Humanoid robots are going to work in factories for NIO and Amazon. Even in the days since that meeting news has come out about researchers at Carnegie Mellon University developing real-time human-to-humanoid teleoperation. This project is based on reinforcement learning (RL) which is an AI/Machine learning technique that teaches a software program to do something by trial and error. This technique, which has been used to teach computers to play video games, is now being applied to teach them how to walk more humanly. It will still be a while before these robots come into mass production, but the pace at which the industry is moving should be noted. And while the committee discusses all aspects of these projects, make no mistake that we are laser-focused on what is happening with hardware.

Currently, robot developers are feeling constraints with the limits of torque in gearboxes that are being used in joints. Committee members are watching this space and watching companies that are out in front in finding solutions. Committee members are also discussing backdrivability—which will be crucial to safety when these types of robots are used next to humans. We are working to bring experts to discuss this in more detail for the AGMA audience. And you are always welcome to join the committee to add to these discussions.

The AGMA Emerging Technology work continues to monitor advancements that may disrupt or positively impact the gear industry. Watch out for our upcoming webinars, and more information on a face-to-face event happening this summer.



Cyberdefense techniques outlined in James McQuiggan's Emerging Technology webinar "AI Steered, Safety Geared: AI's Voyage with Gear Manufacturing."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Cross-Correlation of Design Variables for Epicyclic Systems

Claudio Autore and Massimiliano Turci

The automotive industry pays great attention to the concept of power density and friction losses concerning mechanical transmission systems. Moreover, installation benefits and weight reduction are achieving higher density power. Another important study is about mechanical efficiency: their reduction allows to minimize the heat exchange; the power dissipation problem—produced by friction—must be addressed. Therefore, the gear designer is obligated to incorporate additional cooling systems, or with higher capacity, to address this problem.

Nowadays, electrical units must operate at higher speeds, and they also must manage two-way loading operations, especially hybrid transmissions. The combination of speed and torque must be managed by designers, considering load histories, and evaluating them appropriately.

In this context, the planetary gear systems meet the requirements of compactness and allow obtaining a high power density, especially compared with classic transmission systems obtained by cylindrical gear pairs. High transmission ratios can be reached thanks to these systems; as the target transmission ratio increases the comparison of mechanical epicyclic systems shows even more complex advantages. It is the task of the gear designer to choose the most suitable solution for his application.

Today lacks (focusing on the design of epicyclic gear drive systems) a tool that allows evaluating a series of them with defined constraints. The layout of interest chosen for this analysis involves a fixed ring gear, sun gear in speed out, and carrier as input. The study presented in this paper aims to show a flow of operation that allows the systematic study of gear train families, and it's able to balance the pros and cons through correct visualizations.

Variable objectives and constraints will be defined, as in any optimization process (Ref. 1). The generated variants will then be analyzed with different criteria. The article focuses on the methods of generation of variants and the graphical mode of evaluation of results (matrix plot) (Ref. 2).

Background

First, it is necessary to develop a tool that allows generating multiple design solutions for macro settings of different planetary gears. To make the creation of different solutions, as general as possible, interest variables are imposed in acceptability ranges, with defined constraints. The macro settings information, that the user can decide includes the variability range of the number of teeth of ring and planet, module, numbers of planets, and minimum acceptable number of teeth on the sun. Based on these settings, design solutions are generated—and will be evaluated for the exact definition of the teeth. The study presented shows variables that have been chosen not to change, but by increasing that—and possible combinations accordingly—it is possible to introduce additional ranges to find more sensitivities beyond those chosen.

It should be noted that for the same epicyclic system, two solutions are tested by choice, with planet number of teeth z and z–1. Through the shift profile modification, it is always possible to guarantee both design solutions, achieving different resistance and performance targets—which will be evaluated later.

At this stage, the attention is also directed to the possible behavior of the dynamic system. It is well known the different dynamic behavior of the epicyclic system between sequential or symmetric gear mesh. For a deeper understanding of this, please refer to the specialized text (Ref. 3); summarizing the theme, with different planets meshing with the sun, sun forces arise from the superposition of effects of each gear meshing contact. The mesh sequence, i.e., the phasing between the individual meshes, is an important parameter. The forcing phase allows the defining of two different assembly-forcing conditions, symmetric or sequential mesh sequences. In practice the different layout setting allows to have forcing mostly rotational or translational; the in-depth study of the modal analysis allows the designer to offer a more important overview of the whole system, to detect which are the most dangerous eigenmodes, if rotational or translational modes (Ref. 4).

From general practice, the symmetric solution is preferred, but in reality, it is the dynamic study that defines which solution is the best.

For what concerns this paper today, the mathematical condition that allows to have one solution instead of another is evaluated: it will be a variable associated with each proposal.

One of the most important design engineering choices (Ref. 5) references the basic rack tooth profile, to which the various coefficients of addendum, dedendum, and root radius are linked. In any case, the designer can decide to modify these parameters as preferred. In the current study the standard ISO 53, Type A profile was chosen (Ref. 6). As will be explained later, this is a choice by the author; nothing to prevent the calculation loop, the dimensioning input parameter using the ISO settings, or the self-made values for the parameters in the object.

It should be noted that the study is about macrogeometry, without any reference to the microgeometry goal. The analysis aims to choose the best macro design from which to start for a second microgeometry optimization. For this reason, there is no information about tip relief, crowning of various kinds, and so on.

Another important study concerns the resistance ensured to the system. Usually, the worsening load condition is very different from the load condition used to evaluate and therefore optimize the friction. Even though this study allows evaluating the system strength in a given load point for a certain loading time, it is also possible to develop a rainflow, knowing the load cycle expected by the system. For the specific case of rainflow could be used the approach to the alternate bending factor Y_M calculation proposed by Ref. 7 and 8. In the case of the script, it is possible to indicate the minimum safeties S_H and S_F target to reach, introducing possible variability on the gear face width.

Finally, the definition of the step of increase in the gear center distance to find the optimal profile corrections, that meet the optimization target chosen by the designer. Different targets could be chosen by the user; for each center distance the code automatically chooses the profile shift coefficient with a specific target. This could be the optimal operational goal, as specific sliding or the minimum sliding velocity, or geometrical as minimum/maximum sun gear, or for undercut boundary per gear lastly for minimum top land per gear. As anticipated previously the main target for optimizing epicyclic systems refers to friction losses, so the choice is about the optimal specific sliding. Merging the performance with the required target, for issues related to system resistance can be defined as an optimum value of the best practice of shift profile to set a good response in terms of resistance. It is possible directly to choose the center distance able to respect the best practice in terms of resistance, having the performance target as the main goal.

At this point, it is possible to understand the heart of the script developed that allows the definition of the main geometry for each set of data, obtained from a combination of the aforementioned solutions. At this point, the procedure developed involves switching to commercial software (Ref. 9) where it is possible to run in sequence a series of calculations, acting directly on the design procedure that allows the choice of the key parameter for the definition of the tooth geometry. Then defines the calculation procedure inside a macro.

After initializing the variable previously mentioned, the problem is set by imposing theoretical center distance with a zero shift profile. Until the profile shift coefficient target is achieved—from best practice—the code continues to increase the center distance. Profile corrections can be made by following different targets, as previously depicted. Keeping in mind the attention to the friction, optimization will follow here the optimal specific sliding. Reaching the target, the displacements obtained on all the gears are verified: if these meet the design requirements, the strength verification is performed.

As anticipated, this is performed starting from the minimum project thickness: following incremental steps this thickness will be gradually increased until reaching the minimum safety factors required by the designer.

The verification performed in such places is referred to as bending S_F and pitting S_H; there is nothing to prevent extending expectations based on the application. It is noteworthy that as the face width increases, the face load factor $K_{H\beta}$ factor worsens because it worsens the contact footprint: this phenomenon is considered according to ISO 6336-1 (Ref. 9), changing the load-increasing coefficients.

The code finds the gear's face width that allows the minimum requirements for safety.

At this point begins the performance check: the boundary conditions have been modified where it is wanted to verify the friction losses.

The contact analysis is launched, according to Ref. 10 and 11. It is also possible to launch different boundary conditions to have an efficiency curve. In this study, the friction coefficients are used according to Niemann (Ref. 12); finished the calculation loop the results are stored moving to the next configuration.

The calculation time is minimal: just a few seconds for each configuration; for this reason, it is possible to explore a very high number of technical solutions, not precluding the analysis of any solution.

Discussion

Below is a case of practical analysis, where the procedure previously exposed is tested.

First, the definition of the combinations is given:

z ring		z planet		module			num. planets		z sun
min	max	min	max	min	step	max	min	max	min
40	150	18	51	1	0.5	6	2	3	17

Table 1—Combination input values.

According to the choice shown, there are 71,807 possible combinations, following the above-mentioned procedure.

Recall that no other parameters have been changed in this context, which could strictly be modified by the user depending on the objectives: simply could be modified the combined calculation of the possible variations of input data to generate other case studies. Note that no changes in pressure angle were analyzed in this paper, variations in coefficient of teeth (addendum, dedendum, and root range), lubricant oil, and geometric tolerances: however, also these new variables can be added to the calculation loop without any kind of problem.

Below are the geometric and/or design parameters that have been imposed by choice, and not cycled within the code:

pressure angle	quality ISO	ref. profile	micro geometry	tip diameter allowed	root diameter allowed	x lim sun	step for center distance	face width	S_F min	S_H min
[°]	[-]	[-]	[-]	[mm]	[mm]	[-]	[mm]	[mm]	[-]	[-]
20	8	A	NO	0/-0.2	0/-0.5	0.2	0.05	10/30	1.50	1.20

Table 2—Frozen values by user choice.

Concerning operating conditions, where to perform the calculations is below:

power	speed @ resistance	speed @ performance	required life	amplification factors
[kW]	[rpm]	[rpm]	[h]	[-]
10	2000	5000	1000	1

Table 3—Operational conditions for checks.

Generated the file with all possible combinations, and the study was carried out.

The outputs that are saved for each combination are different, such as geometry—strength (S_H and S_F) and performance—losses—info.

Formulas to calculate S_H and S_F are according to ISO 6336-2, published in 2019. It used method B (analytical approach) for calculation factors.

Formulas for gear geometry are according to ISO 21771 groups.

Gear power losses load dependent PVZP are calculated according to ISO/TR 14179-2, i.e., following the Niemann (Ref. 12):

$$P_{VZP} = F_n \cdot \mu \cdot v_g \tag{1}$$

where:

F_n is the tooth normal force
μ is the friction coefficient
v_g is the sliding speed

Each studied solution must respect geometric constraints; some of them—which if not respected do not allow defining a close geometry—are given below; the user can change them accordingly with his knowledge:

- minimum distance between 2 planets = 0.2 mm
- factor for minimum tooth thickness at tip = 0.2
- coefficient for minimum root gap = 0.2
- coefficient for minimum tip clearance = 0.15
- required transverse contact ratio = 2.0
- maximum permissible value for specific sliding = 3.0
- coefficient for tip clearance = 0.2

Paying attention to the 71,807 solutions proposed, only 2,088 have found a design solution (2.9 percent) and will be stored in the database results.

At this point to view the results it was necessary to develop a tool for analyzing the results that allows to view the relationship between the different variables: it can then be possible to identify the trend and focus on the parameters most important in the definition of the gear geometry specifications based on the target project.

A matrix plot visualization has been developed so that cross-correlations between variables can be displayed: it is easily possible to view the sizes of interest and in this way the results, through x-y canonical graphs. In addition, a series of filters and choices have been introduced, that allows both to underline the variables of interest and to analyze the findings of interest for a given range of variability of one or more variables. It is possible to create databases of design proposals in which to find the most suitable solution for a specific case. Most variables are chosen at the beginning of the study, the greater the database extension.

Before showing the results matrix plot developed in the paper, it is shown that the classic results display interface is used today in *KISSsoft*.

In Figure 1, there are two variables according to the two axes x-y (in the specific minimum root and flank safety factors), reporting a third parametric variable through color (transverse contact ratio in case). Each solution is recalled by a number.

Although this display allows choosing the outputs of interest, focuses the maximum attention on three parameters at a time. Sometimes it is necessary to have more than three variables under control at the same time; with the display as shown in this example, it becomes necessary to change one of the three variables and plot the graph again, losing the previous info. Alternatively, you must save each image separately.

The proposal developed in this paper instead allows for displaying results at the same time. It is possible to choose the number of appropriate variables and get cross-related in between all parameters simultaneously. It is possible to identify possible design trends with project objectives.

The results obtained are not understood as a process of direct optimization, but as a tool to help the designer identify the solution that best meets the design needs.

To better clarify the reading, the results are reported with gradually increased variables.

In Figure 2, the correlations between S_H and S_F are reported, adopting the module as a parametric. The use of the fictitious variable of the case study "case" allows having under control the number of the simulation to which reference is made.

It is then possible to increase variables in output, as well as the output ranges to consider.

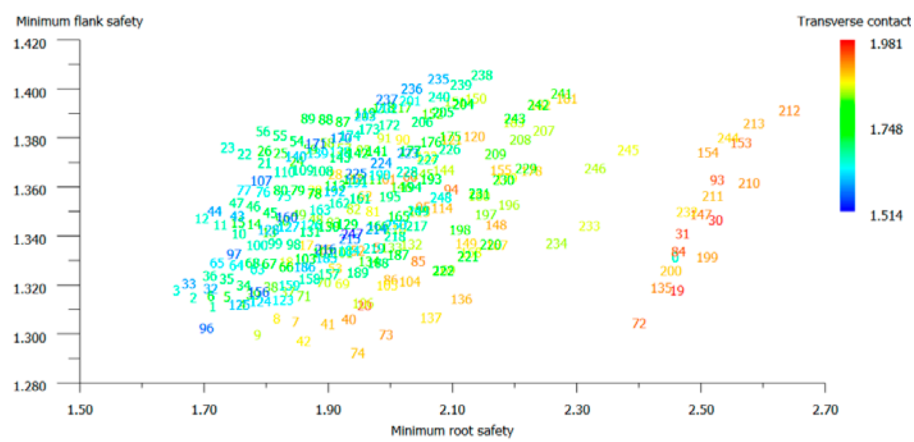

Figure 1—Typical output in commercial software (Ref. 11).

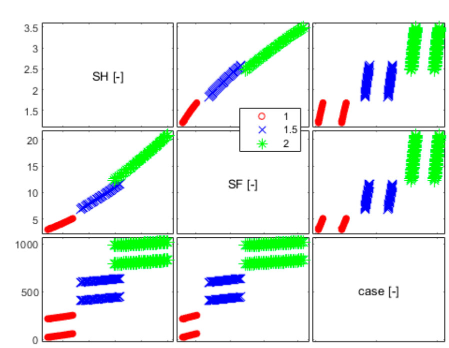

Figure 2—Matrix plot parametrized by module.

Figure 3 shows 5 output results for each solution—not taking into account the fictitious variable "case"—and higher number of module parametrized (1.0:0.5:3.5) than Figure 2 (1.0:0.5:2.0) with only 2 output results, S_H and S_F. The results in the figure below are about transmission ratio, external diameter of the sun and type of dynamic response expected in the system.

It is evident how the user can manipulate it: the visualization here proposed allows finding any correlation trend between variables.

At the same time, it is possible to narrow the ranges as happened in Figure 4, restricting the transmission ratios to be displayed by $\tau < 3$, adding the other output results.

With the procedure indicated, it is possible to store a large number of technical solutions, with an equal level of design accuracy from which to choose the most suitable for this application.

Thanks to this visualization it is easy to evaluate the losses synthetically and identify if there is some parameter driving the loss minimization logic, all while having under control all the design data of every single epicyclic gear train.

To understand the details that can be reached, the inner diameter of the planet and ring have been stored. They may be design limitations in the design phase when choosing such numerical values, to be written to the problems of:

- system dimensions, in the case of the ring diameter;
- support geometry of the planet carrier, in the case of the planet diameter.

In these, are directly available, the analysis of dynamic setting to define that the system is dynamically driven by a kind of forcing instead of another, symmetric or sequential mesh sequence. It is so easy to change the boundary conditions to jump out from the matrix plot, to visualize better the results based on the target. In Figures 3 and 4 the same results shown before are divided by the kinematic forces, in the case 1 instead of 0 for sequential and symmetric solutions respectively.

Moreover, the designer once again chooses the number of constraints. For example, a specific range of transmission

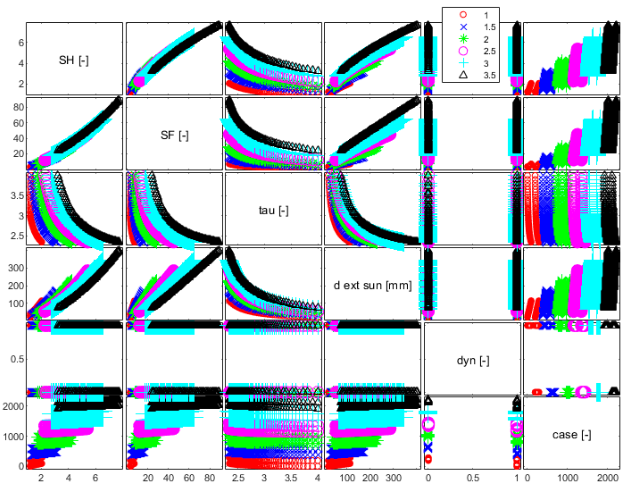

Figure 3—Matrix plot with six parameters.

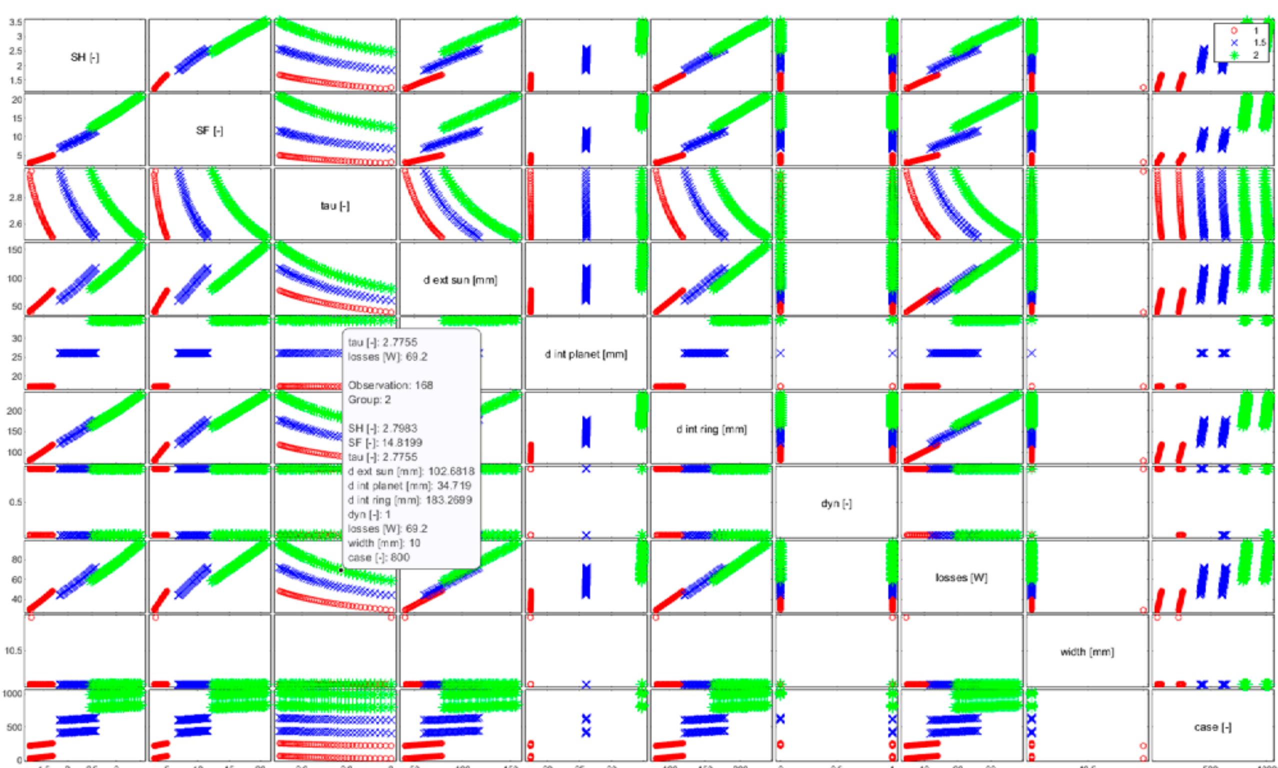

Figure 4—Matrix plot parametrized by module with constrained ranges.

ratio can be simply isolated simultaneously also building the type of dynamic response (1 instead of 0), and the root diameter of the ring teeth (< 250 mm)—representative in part of the overall dimension of the system. This leads to reducing the design solutions that fall into all subsystems.

It is possible to parametrize the results based on what the designer wants to see.

The intention is to show how results can be easily shown, focusing on the designer's interest.

Such charts are to be understood as project maps to help the designer allow the wisest choice of the transmission system to have under control the greatest number of variables.

Future Work

There are therefore many developments that it would be possible to think about.

Firstly, the automation of the entire process analyzed in this paper could allow the development of a user-friendly black-box package, easy to use for the designer.

Secondly the parametrization of system stiffness, on a geometric basis, allows for calculating the dynamic response of the system; it is in this way to identify which of the forcing dynamics of the system satisfy the designer's choice (Ref. 5).

The same calculation has already been implemented for the calculations of external gears: joining the two works would allow to extend the analyses also for complex transmission systems. Complex systems could also be considered for a multistage epicyclic gear system.

Conclusion

This paper shows a methodology to extensively evaluate different designs of epicyclic gear systems.

As outlined, no choice is required on the part of the designer who is free to probe all design variables.

The study was divided into different steps well defined:

1. Selection of variables to be included in the study and the automatic generation of all mathematically possible combinations;
2. Automatic design of each epicyclic system according to geometric constraints and minimum security requirements guaranteed;
3. Results in visualizations according to filtering logic and results sampling.

Acknowledgments

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Claudio Autore earned his master's degree in mechanical engineering in 2013, and a Ph.D. in 2016 at University of Rome Tor Vergata. He joined Ferrari GT in 2014 in the ICE Simulation Department. In 2017 he moved to Ferrari F1 as Team Leader ICE Dynamic Simulation Department. Since 2020 he has been ICE F1 Geartrain Technical Leader.

Max Turci is a consultant in gear and cam mechanisms design. He is the team leader of the Italian technical staff of KISSsoft. His experience is primarily in the development of computational models for industrial gearboxes and vehicle transmissions. He has also served on the AGMA worm gear committee.

How Many Speed Ratios for Electric Cars? One Example.

Prof. i.R. Dr.-Ing, Dr.h.c. Bernd-Robert Höhn and
Dr.Ing. Yingying Zhang

Transmissions are often considered a "necessary evil" in driveline systems. Although often considered cumbersome, transmissions are indispensable when the motor speed does not match the required speed of the machine being driven. Additionally, the efficiency of the driveline can be improved if the overall efficiency—the multiplication of the efficiency of the engine and transmission—of the driveline system comes into focus (Refs. 1–4). This has consequences in the automobile industry where eight to nine gears are normal in an automatic transmission with an ICE (Refs. 5, 6). Based on well-established principles taught in many universities, transmission designs are calculated to include necessary starting gear ratios, high-speed gear ratios, and one or more overdrive gear ratios to reduce fuel consumption by lowering the internal combustion engine speed.

How will transmissions be designed for electric motors in a car? We have the same situation: the driving motor's efficiency map influences the transmission's design. Electric motors also have efficiency maps, but these are fundamentally different from those of internal combustion engines. Alone the knowledge, that electric motors don't need a clutch or torque-converter for starting gear ratio and that an electric motor has torque from the speed 0 is enough to make only one gear between the electric motor and tires. Although single-gear transmissions are commonly used in mass-produced electric vehicles, they do not meet future requirements for the interface between the electric motor and the tires. A multispeed transmission will not necessarily be heavier than the existing 1-speed transmission in actual cars.

Maps for Electric Motors

Figure 1 shows an ideal efficiency map for an electric motor, which is designed for a car application. All types of electric motors have nearly the same characteristics. Torque from speed 0 and a long range of speed with nearly constant power. This range can be different from the types of electric motors and depends on their design. You don´t need a clutch or a torque converter for the gap between speed 0 for the car and the minimum speed of an ICE. That is a common problem of ICEs (like gasoline, diesel, or e-fuels), they are not able to deliver torque below their idle speed. The operational range of electric motors with constant power output plays a significant role in transmission design.

$$\Phi_{E-Motor} = \frac{n_{max}}{n_{T_{max}}} = \frac{\text{maximum speed}}{\text{maximun speed for maximum torque}} \quad (1)$$

where
$\Phi_{E-Motor}$ is ratio between maximum speed and maximum speed for maximum torque
n_{max} is maximum speed [min^{-1}]
$n_{T_{max}}$ is maximum speed for maximum torque [min^{-1}]

Another point is the best efficiency of electric motors. How Figure 1 shows that this point will be below the maximum speed of the electric motor n_{max} and for this ideal example by (roughly) $n_{\eta max}=2 * n_{T_{max}}$, that means for this example by much lower than the maximum speed of the electric motor. With this ideal map, the method will be introduced to calculate the starting gear ratio, the highspeed gear ratio, and the overdrive gear ratio and with these values deliver the ratio range for the transmission for electric cars.

Efficiency deteriorates at constant vehicle speeds when operating in the high-speed range of electric motors. The efficiency of a constant speed of the car will become more important in the future even in Germany with (now!!) no speed limit for highways. If you drive at a constant car speed of 100 km/h you need only 20 kW for this example, which means much less than the maximum power for this electric motor. The overall efficiency η_{ov} can be calculated with Equation 2.

$$\eta_{ov} = \eta_{mot} \cdot \eta_{transmission} \quad (2)$$

Overall efficiency affects the amount of electric power needed, which in turn determines the battery storage requirements. That means the range for electric cars can be very much improved if you increase overall efficiency. More detail and an explanation for the overall efficiency and the range increase can be seen in Refs. 1–4.

Characteristic Values for Ratio and Ratio Range for Transmission

Starting Gear Ratio

The starting gear ratio $i_{start\ E}$ can be calculated from the required torque for one axle (or more for four wheel-driven cars) and the torque of the driving motor. You or the applicant decide if you use the normal torque or the peak torque of your electric motor. The axle torque depends on the inertia of the electric motor and the driveline; more detail can be found in Ref. 7, this factor is called φ.

$$i_{start\ E} = \frac{T_{axle}}{T_E} \cdot \varphi \quad (3)$$

where
T_{axle}=torque at axle [Nm]
T_E=torque of electric motor [Nm]
φ=inertia factor (Ref.7)
with axle torque calculated out of the slipping limit of the tires

$$T_{axle} = m_{axle} \cdot \mu_{wheel} \cdot r_{wheel} \cdot g \quad (4)$$

where
m_{axle}=mass of axle [kg]
μ_{wheel}=friction coefficient tire-street
r_{tires}=radius of tires [m]
g=earth acceleration [m/s^2]

And the inertia factor φ for this example, which is defined from Lechner/Naunheimer (Ref. 7):

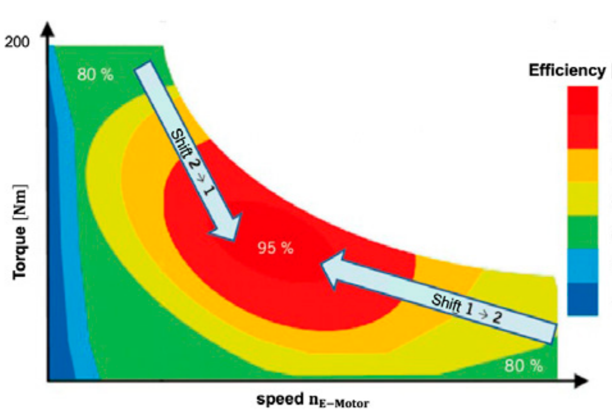
$$\varphi \approx 1.2 \quad (5)$$

For this example, the mass for one axle will be named to 1,100 kg and the friction coefficient for the contact rubber (wheel) to street will be named to $\mu wheel$ = 1 and the radius of the tires should be 0,3 m, for this example the istart E can be calculated with Equation 3 to:

$$i_{start\ E} \approx 19{,}4 \quad (6)$$

for T_E, the value will be taken from the ideal motor out of Figure 2, $T_E \approx$ 200 Nm. For the peak torque of the electric motor, the value becomes smaller.

Figure 3 shows the ideal electric motor in a car with a given driving resistance curve (one can use a lot of parameters, which are valid for this curve). The driving resistance curve shows the required power of a car versus car speed. The slipping limit (maximum power) can be calculated with the



Source: ATZ Nr: 10/2017

Figure 1—Efficiency map for an ideal electric motor.

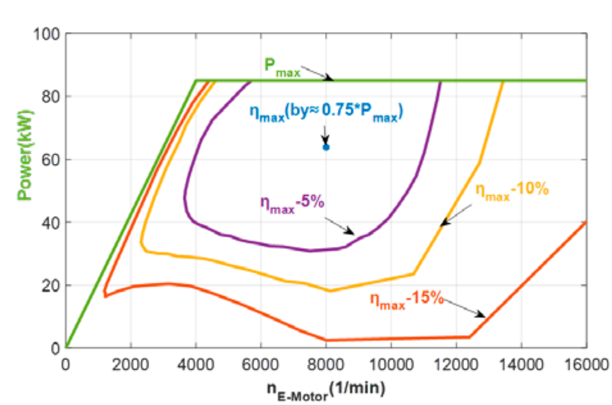


Figure 2—Efficiency map of an electric motor with 85 kW ref. to Figure 1, incl. power unit.

multiplication of the maximum torque at the axle with the speed of the tires. You can see that, with a starting ratio of about $i_{start\ E} \approx 16$, the car can only drive about $v \sim 105$ km/h. Whether this value $i_{start\ E} \approx 19.4$ will be used for maximum acceleration or hill climbing or hill climbing with trailer has no influence. Not until a speed of about 26 km/h can this car accelerate with slipping limit, for acceleration at higher speed you need more power, that is shown in Figure 3.

High-speed Gear Ratio

The high-speed gear ratio i_{HE} can be calculated kinematically (not with torque like starting ratio). The values can be calculated out of maximum speed of the electric motor (n_{max}) and the required maximum speed of the car (speed of the tires $n_{wheelvcar}$).

$$i_{HE} = \frac{n_{max}}{n_{wheelvcar}} \tag{7}$$

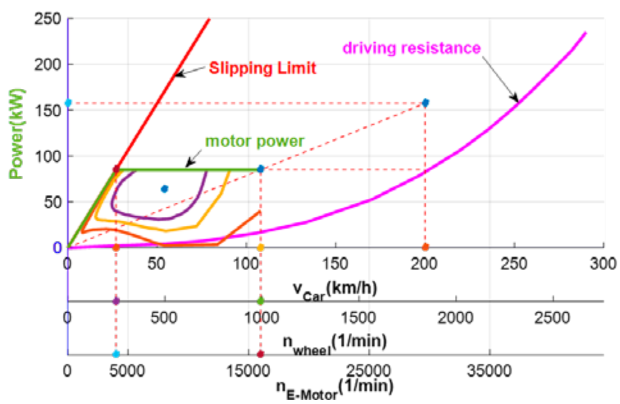


Figure 3—Efficiency-map of an electric motor with a starting ratio for cars.

The theoretic possible maximum speed of the electric motor is 16,000 min^{-1} (for the example out of Figure 2) and for the maximum speed of the car (for this ideal electric motor with 85 kW, see Figure 4) with Equation 6 can the value calculated to the highspeed gear ratio:

$$i_{HE} \approx 9 \approx \left(\frac{16000}{1800}\right) \tag{8}$$

Of course, one can use other high speeds for cars too.

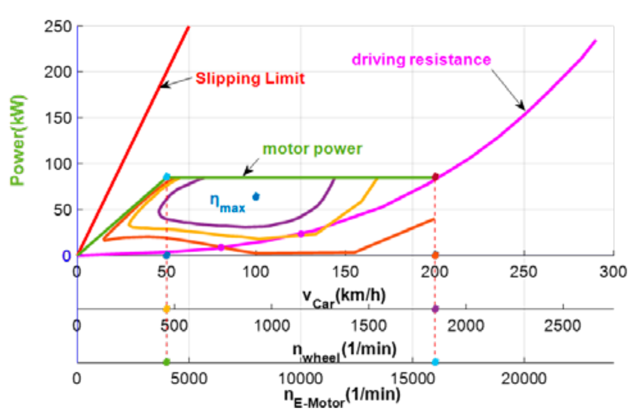


Figure 4—Efficiency-map of an electric motor with a high-speed gear ratio for cars.

With these two values for starting gear ratio and high-speed gear ratio the ratio range of the transmission can be calculated to:

$$\Phi_D = \frac{i_{start\ E}}{i_{HE}} \approx 2,2 \tag{9}$$

Overdrive Gear Ratio

The overdrive gear ratio for cars with ICEs can be established with the wish to improve the overall efficiency with Equation 2 and to reduce fuel consumption. For ICEs, this map can be derived from the be-map (specific fuel consumption by an ICE). With one or more overdrive gears you can reduce fuel consumption for lower speeds than the maximum speed of cars.

In principle, you can define overdrive gears for electric cars in the same manner as ICEs. Here you can reduce the electric energy (stored in a battery) the customer requires for mechanical power with better overall efficiency according to Equation 2. Because the efficiency map for electric motors is totally other than for an ICE the following method is proposed. For this ideal electric motor will be proposed in Figure 5 that the driving resistance curve should be tangential to the curve $\eta_{max-5\%}$. This proposal is founded because the theoretical possibility to reduce the electric motor speed more, that means the driving resistance curve should go through the maximum efficiency point (possible for this example for a car speed of about 180 km/h) will result a very low value of the overdrive gear and a very high value of the ratio range for the transmission.

With this proposal you will get Figure 5, marked with x for a car-speed of 150 km/h and a speed for the electric motor of about $n_{E-Motor} \approx 9700$ min^{-1}:

$$i_{od} = \frac{n_{E-Mot\ \eta\ max-5\%}}{n_{wheel}} \tag{10}$$

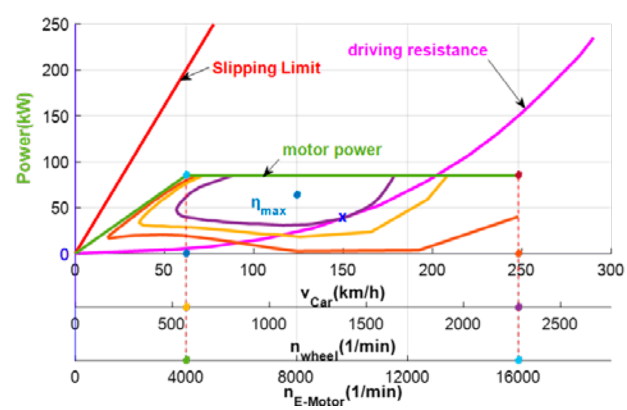


Figure 5—Efficiency-map of an electric motor with an overdrive gear ratio for cars.

and for this example:

$$i_{od} = \frac{9700}{1350} \approx 7.2 \tag{11}$$

and a total ratio range for the transmission Φ_{tr}:

$$\Phi_{tr} = \frac{i_{start\ E}}{i_{od}} = \frac{19,4}{7,2} \approx 2.7 \tag{12}$$

Ratio Range for Transmission

The ratio range for this example can be derived out of driving resistance curve for cars and efficiency-maps for the engines. This can be electric motors or ICEs. For calculation of the ranges following equation can be used:

$$\Phi_D = \text{ratio range for driving} = \frac{i_{start\ E}}{i_{HE}} \quad (13)$$

$$\Phi_{od} = \text{ration rand for overdrive} = \frac{i_{HE}}{i_{od}} \quad (14)$$

$$\Phi_{tr} = \text{ration range for transmission} = \frac{i_{start\ E}}{i_{od}} = \Phi_D \cdot \Phi_{od} \quad (15)$$

Two-Speed-Automatic Transmission for Electric Cars

If an electric car is designed to have only two ratio ranges, the high-speed gear ratio becomes less relevant, because electric motors can produce the maximum power by smaller and lower speeds (Figure 1 and Figure 2). The range Φ_{tr} for this example is very high and the step from first gear to the second gear are unusual and for shifting elements too high. Therefore, it is recommended to use the peak-torque of electric motors to reduce the ratio range. The value of the starting gear ratio will be decreased, though that Φ_{tr} will become much smaller and suitable for shifting elements. Nevertheless, the ratio range for transmission is smaller than for all known electric motors (Equation 1), which means, if you shift at the high speed of the electric motor after the shifting process you have the same power as before. For calculation of brakes/clutches you should have a look at the patents (Refs. 8, 9).

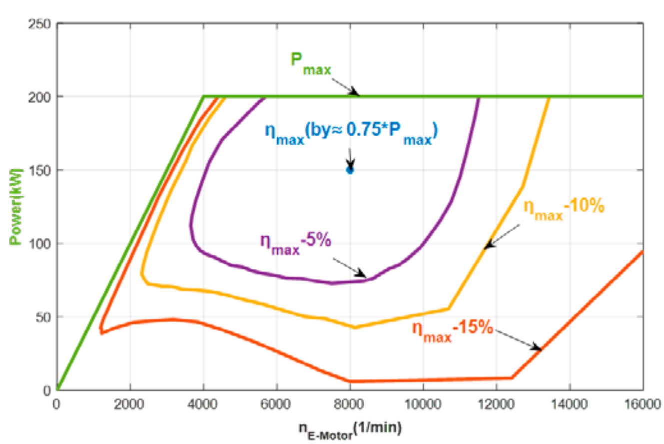


Figure 6—Efficiency-map of an electric motor with 200 kW ref. to Figure 1, incl. power unit.

In Figures 6 and 7, the ideal motor is scaled up to a power output of 200 kW, using the data from either Figure 1 or Figure 2. For this particular electric motor, the required gear ratio for driving is approximately 1, eliminating the need for a second ratio. This is because the car can achieve speeds exceeding 200 km/h using just the starting gear, as demonstrated in Figure 7. If you aim for higher overall efficiency through overdrive, a two-speed automatic transmission would be beneficial.

Figure 8 displays the overall efficiency, calculated using Equation 2. Compared to the smaller 85 kW electric motor, the efficiency has decreased by about 5 percent because the motor's optimal efficiency point is not achievable at a constant driving speed. Data points for speeds of 80 and 130 km/h (50 mph and 85 mph) are plotted in Figures 7 and 4. For the electric motor with 85 kW the value of η is $\approx \eta_{max}$ − 10 percent, for 200 kW this value is η is $\approx \eta_{max}$ − 15 percent. In the calculations using Equation 2, the transmission efficiency has only a minor impact. When comparing the efficiency of current mass-produced models with the patented example, it is evident that transmission efficiency does not have a significant influence, although it is better than a one-speed transmission.

For the curves in Figure 8, the efficiency of the transmission was taken constant (equal for both transmissions), because losses in the open synchronization (Ref. 12) exist and they are about the same value as the lower losses of the chosen planetary transmission. Figure 8 shows only the difference of η_{mot} (Equation 2) between the different electric motors with 85 kW and 200 kW. The advantages in efficiency are direct advantages in the range of electric cars.

Here it can be seen that "high-powered" cars have nearly 5 percent lower range by the same size of the energy-storage (battery). High-powered cars are for example the B-class (like corsa/ fiesta /polo) with 200 kW power. This class should be powered by 85 kW and 2-speed-automatic transmission, then you have advantages in the range of these classes and the same hill-climbing possibility and the same acceleration until about 25 km/h. That means nearly no disadvantages.

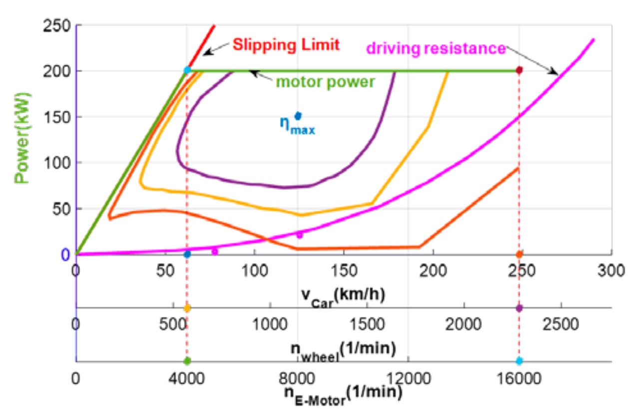


Figure 7—Efficiency-map of an electric motor (200 kW) with a starting ratio for cars.

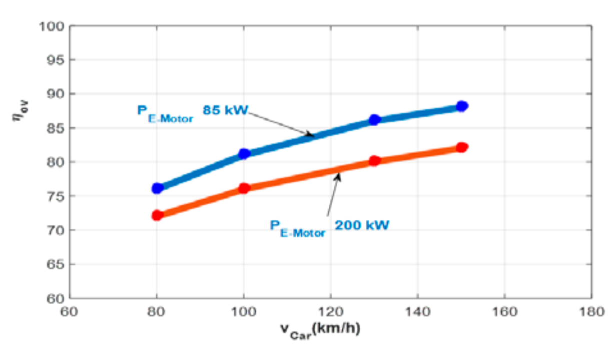


Figure 8—Overall efficiency for constant speed for different power of the electric motors.

The Example for the 2-Speed Transmission

Figure 9 shows the sketch out of the patent. The electric motor is connected to the sun 1 of the two used planetary transmission. The first gear (starting gear) uses the planetary transmission 1–2 with a stepped planet, the second gear (highspeed-gear) is the "normal" planetary transmission with 1–2. That means the carrier is by both gears connected to the output-shaft. With the two brakes, one is connected to the smaller ring-gear 2' the other one is connected to the bigger ring-gear 2. For both planetary transmission the efficiency can be calculated with (Ref. 11) with the working sheets for η_{1s}. One part of the power is transmitted as clutch-power without any losses (Ref. 11).

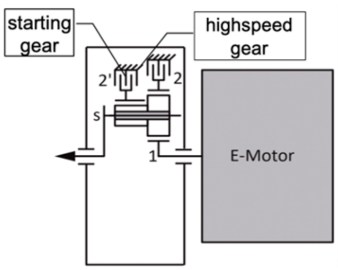


Figure 9—Sketch of the planetary transmission out of Pat. PCT/EP2020/079280.

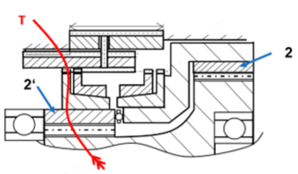


Figure 10—Starting gear (1. Gear, $i_{start\ E}$) of the 2-speed automatic transmission.

Figure 10 illustrates the flow of torque in the first gear, characterized by the initial gear ratio $i_{start\ E}$. The smaller ring gear is secured to the housing using a brake mechanism, which could be either a dog-clutch or a spline. The stepped planetary gears transmit torque from the first input shaft 1, which is connected to the electric motor, to the output shaft that serves as the carriers for both transmissions.

Figure 11 depicts the flow of torque during the gear shift from first to second gear. During this shifting process, the electric motor generates no torque, resulting in a net electric torque of zero. The synchronization system should possess the same maximum torque capacity (T_{nmax}, as shown in Figure 13) as the electric motor when operating at maximum speed. If the motor reaches this maximum speed, the customer will not experience any changes in the torque output on the output shaft. During this process, the torque required to drive the car is generated by the deceleration of the electric motor's inertia. For the customer, the source of the torque—whether it comes from the deceleration of inertia or from electric torque—is irrelevant. The only remaining question is the duration of this time period. Initial calculations, using the inertia values of an actual electric motor, indicate that the time required for torque 0 synchronization is within acceptable limits. This implies that a hydraulic system, complete with pumps and valves typically found in a standard automatic transmission, is unnecessary. The details of this shifting process can be executed entirely through electromechanical means, as outlined in patent PCT/EP2020/079280 (not shown here) (Ref. 9).

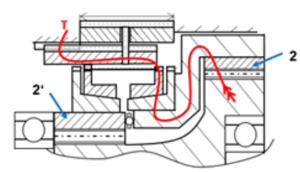


Figure 11—Torque flow while shifting process from 1 to 2 gear (starting gear to high-speed gear).

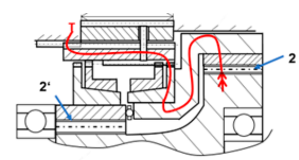


Figure 12—Torque flow in 2 gear (high-speed gear, i_{HE}).

Figure 12 shows the torque flow in the 2 gear (the high-speed gear, i_{HE}), here the bigger ring-gear is connected to the housing, which means the ring gear 2 (see Figure 9) stands still and the torque/power will be transmitted from sun 1 with only one planet (the bigger one of the stepped planets) to the carrier (output shaft). After the shifting process (Figure 11 and Figure 12), when no difference speed between ring gear 2 and the housing is given, you can shift the ring to the shown position, and you have the dog clutch (spline) between ring gear 2 and housing. For this position, any torque from the electric motor can be transmitted to the output shaft.

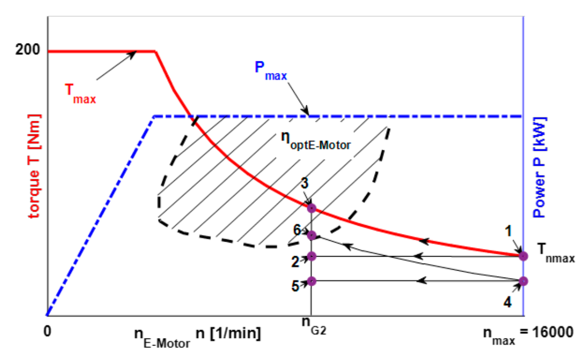


Figure 13—Shifting process for the electric motor, no torque interruption while shift from 1 to 2 gear with the synchronization (torque capacity like torque from the motor for maximum speed n_{max}, see Figure 1).

Shifting process 1 → 2 is proportional to the constant axial force for synchronization. In this case, the torque capacity of the synchronization has the same value as the maximum torque T_{nmax} of the electric motor with maximum speed n_{max}. For partial load—shifting 4 → 5—the axial force of the synchronization is smaller than the 1 → 2 process. In 2 or 5 no difference in the synchronization is valid and the dog clutch transmits any torque of the electric motor (Figure 12).

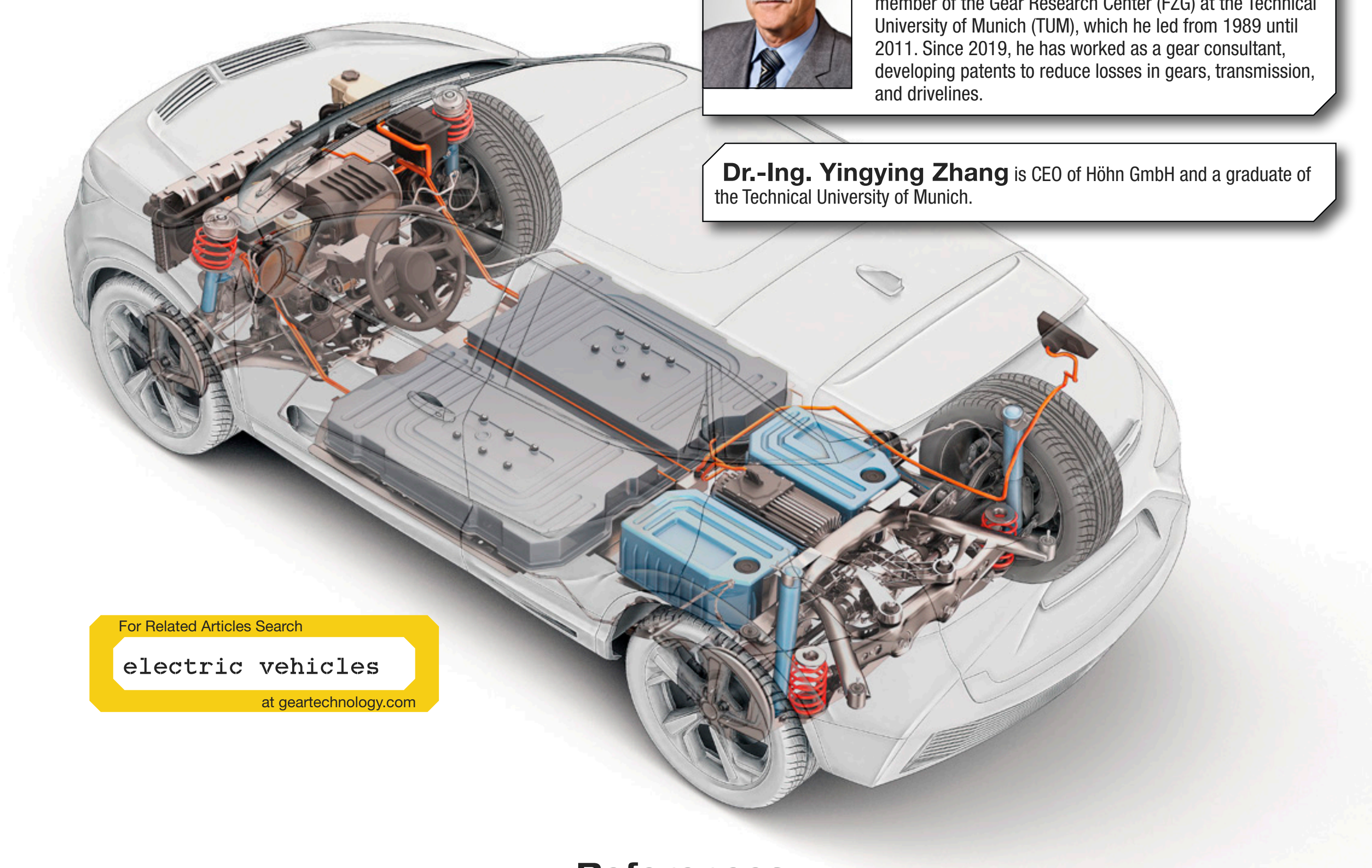
Conclusion

With the shown method the advantages of 2-speed automatic transmission for cars with electric motors you can calculate the ratios and the ratio-range for a 2-speed-transmission. You can make a significant improvement in the efficiency and range of the car for less electric power. The use of this 2-speed-automatic-transmission make sense for passenger cars with electric power < 100 kW and for trucks (all sizes). The example illustrates a transmission that uses an electromechanical system for shifting, eliminating the need for a hydraulic system, and minimizing torque interruption. Though this example is thought for passenger cars and for trucks in general. The summary can be:

2-speed-automatic transmission are recommended for passenger cars with power < 100 kW and for all trucks.

Prof. i.R. Dr.-Ing, Dr.h.c. Bernd-Robert Höhn retired in 2011 but remains a member of the Gear Research Center (FZG) at the Technical University of Munich (TUM), which he led from 1989 until 2011. Since 2019, he has worked as a gear consultant, developing patents to reduce losses in gears, transmission, and drivelines.

Dr.-Ing. Yingying Zhang is CEO of Höhn GmbH and a graduate of the Technical University of Munich.



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AGMA 2024 Annual Meeting Announcements

The American Gear Manufacturers Association (AGMA) announces its Board of Directors changes, AGMA Foundation Board of Trustee appointments, and Award Winners at the 2024 Annual Meeting in Napa, CA.

AGMA Board

AGMA Officers and Board of Directors

New Officers

The following people were elected to serve as Board Officers through 2028:

- Chair, Technical Division Executive Committee
  Jason Daubert, Chief Gear Engineer, FLSmidth Cement USA, Inc.
- Chair, Business Management Executive Committee
  Michelle Maddox, Sales & Business Development, B&R Machine & Gear Corp.

Incoming Board of Directors

The four new Directors were elected to serve a three-year term, from 2024 to 2027.

- Andreas Blind, President, Star SU
- Jack Conway, President, Atlanta Gear Works, Inc.
- Shawn Liverseed, VP & CFO, NORD Drivesystems USA
- Justin Michaud, CEO, REM Surface Engineering

Outgoing Board of Directors

The following Directors were honored with the AGMA Board of Directors Award for their years of service to AGMA from 2021 to 2024:

- Craig Burriss, President, Amarillo Gear Co., LLC
- Brian Coclich, President & COO, CGI, Inc.
- Adam Gimpert, President, Helios Gear Products
- Mushtaq Jamal, Director, Engineering & Business Development, Bevel Gears India

"AGMA would not be where it is today without the passion and diligence of its Board of Directors," said Matthew E. Croson, President, AGMA. "I want to thank the outgoing Directors for their wisdom and guidance during the pandemic and for helping AGMA maneuver through the tough economic conditions that followed. I have full confidence in our new Directors as AGMA focuses on programs to improve the gear industry at home and forge new partnerships with like-minded associations and organizations abroad."

AGMA Foundation Board of Trustee Appointments

The AGMA Foundation announces changes to its Board of Trustees at the AGMA Members' Meeting.

New Trustees

The following people were appointed to serve a three-year term, from 2024 to 2027.

- Lisa Engesser, Reishauer
- Joe Goral, Bourn & Koch
- Scott Yoders, Liebherr

"The Foundation continues to serve the gear industry by providing funding through their four pillars: education, workforce, scholarship, and emerging technology," stated Executive Director, Mary Ellen Doran. "These new Trustees will help us make key decisions in how we can have a greater impact on the workforce over the next three years. I look forward to their contributions."

2024 Award Winners

AGMA honored three members at the annual meeting. Two individuals received the Lifetime Achievement Award, and one received the Hall of Fame Award.

Lifetime Achievement Award Recipients

Sulaiman Jamal, Managing Director, Bevel Gears India, and Andrea Scanavini, President (retired), Somaschini, both were recognized with their Lifetime Achievement Awards for their continuous dedication and contributions to the industry and association.

The Lifetime Achievement Award is given by AGMA to rare individuals who have given years of service to AGMA and the global gear industry. To receive this award, one must have demonstrated superior vision and leadership, generously given extensively of their time and skills, freely shared exceptional knowledge, and experience with colleagues, tirelessly worked to advance the gear art, demonstrated wisdom in pursuit of industry consensus, achieved the respect and admiration of peers, and been available whenever needed for the advancement of the AGMA and the global gear industry.

Hall of Fame Award Recipient

David Goodfellow, President & CEO (retired), Star SU, received the Hall of Fame Award for his career-long dedication to the association and the industry. AGMA's most prestigious award, the AGMA Hall of Fame award honors the visionaries who have paved the way for the practices and products of the gear industry as we know them today. Recipients are pioneers who have influenced the gear industry with their inventions, practices, and leadership.

Other than the founding companies of AGMA, only one other individual has received the Hall of Fame award since its inception in 2016.

"AGMA is so much more than the sum of its parts thanks to overwhelming dedication from members like David Goodfellow, Sulaiman Jamal, and Andrea Scanavini," said Matthew E. Croson, President, AGMA, "And it is our pleasure to honor them with these well-deserved awards. Their actions and participation make AGMA an association that promotes the growth and mentorship of its members and ensures the health and comradery of the gear industry for years to come."

agma.org
agmafoundation.org

APRIL 23–28

Control 2024

Control 2024 (Stuttgart, Germany) offers the most up-to-date technologies from the fields of vision technology, image processing, sensor technology, as well as measuring and test technology and quality assurance. "Measurement, testing, inspection, evaluation, documentation-end-to-end solutions for these functions are required everywhere because more and more data is being captured, analyzed, linked, and fed back to the respective systems to achieve transparency and consistency. This is why software and intelligent evaluation algorithms are playing an increasingly important role," explains Fabian Krüger, project manager.

geartechnology.com/events/5088-control-2024

MAY 6–9

Cleanpower 2024

Cleanpower 2024 (Minneapolis) grows businesses by gathering key decision makers and stakeholders across the wind, solar, storage, hydrogen, and transmission industries for discussion, deal making, networking and a whole lot of fun. The trade show not only brings together the different technologies that make up the renewables mix; onshore wind, offshore wind, solar, storage, and transmission but also the different segments within the industries; manufacturers, construction firms, owner operators, utilities, financial firms, corporate buyers and more. Cleanpower will feature the latest products, services and technologies coming to the renewable energy industry.

geartechnology.com/events/5089-cleanpower-2024

MAY 6–9

Automate 2024

Between intimate workshops with industry giants, keynotes, networking events, innovation competitions and live demonstrations, Automate 2024 (Chicago) offers comprehensive automation education and cutting-edge robotics, vision, AI, motion control and other technologies. Automate delivers the latest innovations in manufacturing automation technology from more than 600 leading exhibitors. Each day also offers inspirational keynote sessions and theater presentations to help attendees find the best solutions for their unique business needs.

geartechnology.com/events/5091-automate-2024

MAY 15–16

CTI Symposium USA 2024

CO2 reduction is critical for automotive drivetrain. Here the battery electric drive using renewable energy is the focus. What can we do to increase efficiency and reliability, reduce cost and at the same time reduce upstream CO2? At CTI Symposium USA 2024 (Novi, MI) the automotive industry discusses the challenges it faces and promising strategies. Latest solutions in the fields of electric drives, power electronics, battery systems, e-machines as well as the manufacturing of these components and supply chain improvements are presented. For the bigger picture market and consumer research results as well as infrastructure related topics supplement the exchange of expertise.

geartechnology.com/events/5064-cti-symposium-usa-2024

MAY 19–23

2024 STLE Annual Meeting and Exhibition

STLE is celebrating 80 years of technical excellence and innovation during the event. The STLE Annual Meeting & Exhibition (Minneapolis) will feature over 500 technical presentations, a trade show with over 100 exhibitors, a Commercial Marketing Forum, 13 industry-specific education courses, discussion panels on technical and market trends, and more. "This year, we're excited to offer two new panel discussions on topics that are key to the tribology and lubrication engineering community," said Rebecca Lintow, CAE, STLE executive director. "One panel will highlight various sustainability topics from top industry experts, including standards, regulations, technologies, and best practices. The other panel will feature notable women in the lubrication industry and insights about their career paths and experiences."

geartechnology.com/events/5092-2024-stle-annual-meeting-and-exhibition-registration

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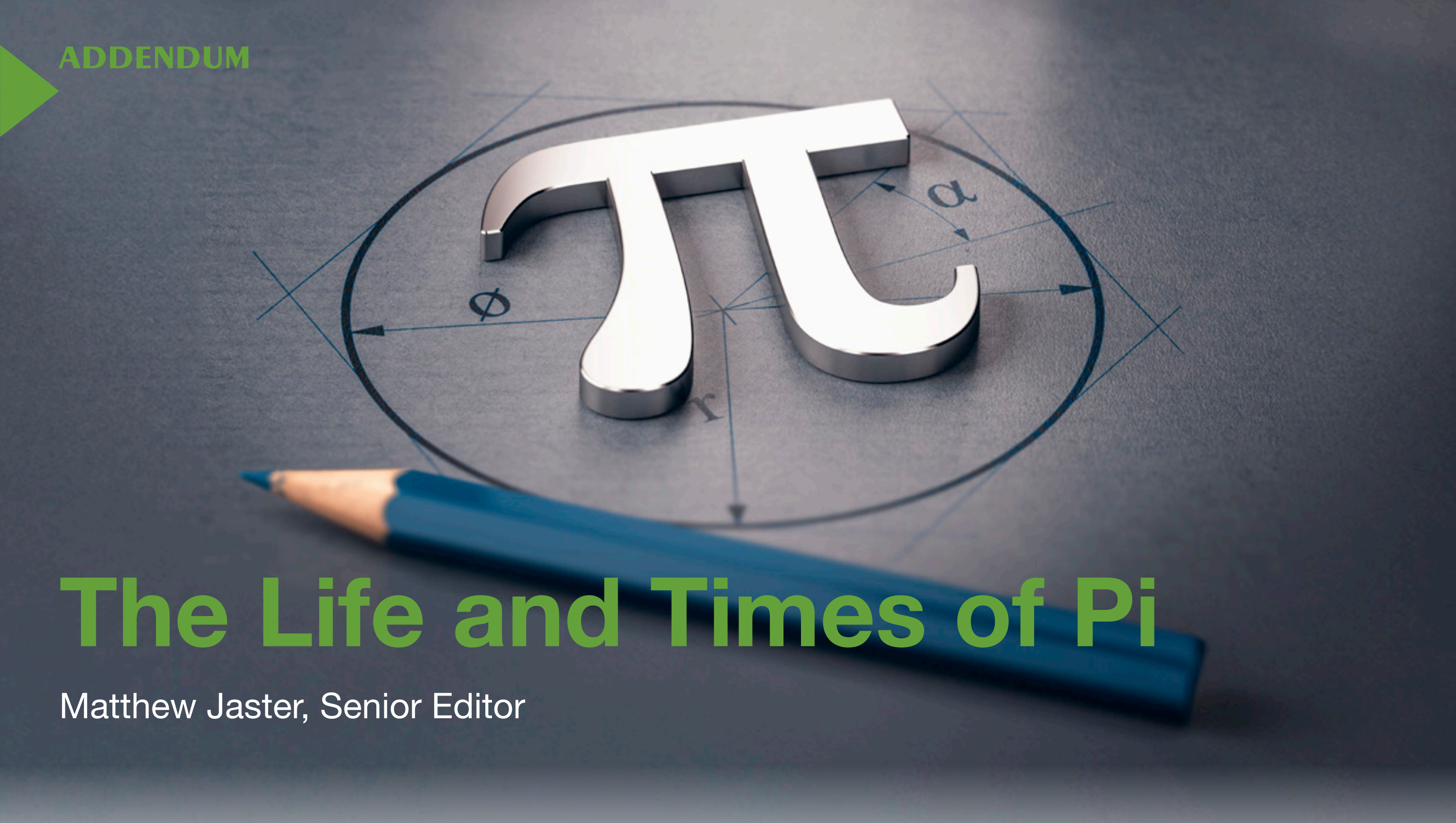

The Life and Times of Pi

Matthew Jaster, Senior Editor

Pi Day took place on March 14, 2024. Our friendly neighborhood constant is used in engineering to determine the dimensions of gears, wheels, and pipes. Pi is also used in computer science to generate random numbers for cryptography, simulation, and gaming. With a tip of the cap to math enthusiasts, we offer a quick cheat sheet to pi and its fascinating history.

Pi has been known since ancient times The first recorded approximation of pi was done by the ancient Egyptians around 1650 BC. They estimated the value of pi to be around 3.16. The ancient Babylonians also had a similar approximation, as did the ancient Greeks. The Greek mathematician Archimedes is credited with being the first to accurately calculate pi using a geometric method around 250 BC.

The symbol for pi (π) was first used by Welsh mathematician William Jones in 1706. However, it was not widely adopted until the 1730s when Swiss mathematician Johann Lambert started using it. The symbol was chosen because it is the first letter of the Greek word for perimeter (περιμετρος).

Pi is an irrational number, which means that it cannot be expressed as a finite decimal or fraction. Its decimal representation goes on forever, without repeating. This property has intrigued mathematicians for centuries, and many have attempted to calculate pi to as many digits as possible. As of 2021, the most accurate calculation has been done up to 62.8 trillion digits!

Filmmaker Darren Aronofsky (*Requiem for a Dream, The Fountain, Black Swan*) made his feature film debut in 1998 with *Pi*, a psychological thriller following an obsessed mathematician who believes everything in nature can be understood through numbers.

Pi Day began in 1988 when Larry Shaw, a physicist at the Exploratorium in San Franscico celebrated the calculation on March 14 (3.14). Fittingly, it's also Albert Einstein's birthday. Shaw originally celebrated "Pi Day" by simply eating pies and discussing mathematical constants. It would evolve to include a parade, a pi shrine, the eating of pies (pizza and desserts), and more.

Pi Day was recognized as a national holiday in 2009 and is internationally celebrated.

Not only is pi irrational, but it is also a transcendental number. This means that pi is not a root of any nonzero polynomial equation with rational coefficients. In simpler terms, it cannot be expressed as the solution to any algebraic equation with rational coefficients. This property makes pi even more mysterious and intriguing.

Nathan Mihm, a Mathnasium lead instructor in Eagan, MN, has memorized over 500 digits of pi and continues to learn more for each Pi Day. Nathan developed a passion for mathematics in 9th grade as a participant in the Eagan High School mathematics team.

Practical uses for pi include determining tank sizes for heating and air conditioning systems, calculating the Earth's circumference (take that flat earthers), accurately pointing an antenna toward a satellite, and determining the size of paper rolls to print this very magazine!

My personal favorites include pi helping NASA engineers design the parachute for Mars landings, searching for exoplanets outside our solar system and peering below Jupiter's clouds to estimate the volume of materials in the planet's atmosphere.

In World War II, the Allies used pi to encode messages sent between the US and the UK. They would use pi digits to represent letters, numbers, and other characters.

If March 14th truly represented pi, it would never end. Many would be stuck in a cold, gray-clouded void between winter and spring filling out endless NCAA tournament brackets and consuming far too many Shamrock Shakes.

(facts provided by *mathnasium.com*, *nasa.com*, *exploratorium.edu*)