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STATE OF THE GEAR INDUSTRY

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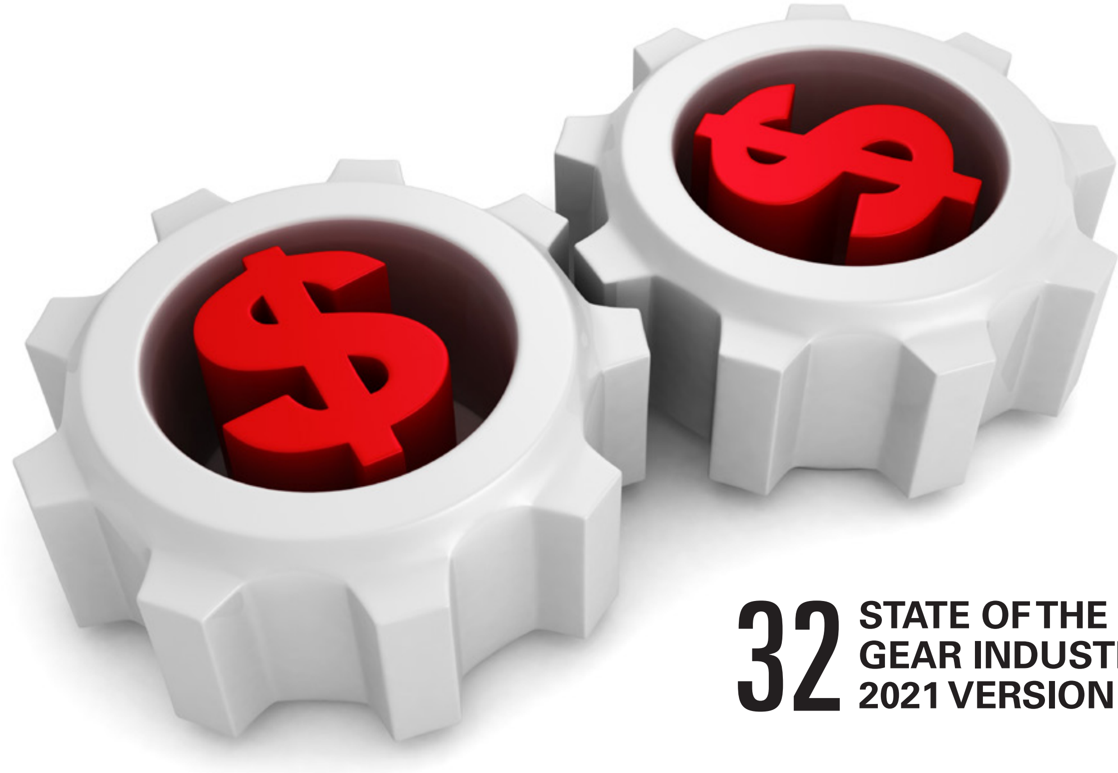

features

technical

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departments

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Electromobility with Klingelnberg

Research on new zero-emission drives is currently being conducted all around the world. Machine-manufacturer Klingelnberg is also working hard in this area in an effort to deliver concrete solutions for current and future demands. Learn more here:

Electromobility with Klingelnberg (geartechnology.com)

Power Skiving with Seco Tools

Gears can be manufactured without specialized machines, with the appropriate software, tools, and machining centers. The complete component can be finished in one machine and in one set-up, which shortens production time, improves quality, and reduces handling and logistics costs. Learn more here:

Power Skiving with Seco Tools (geartechnology.com)

Gear Talk with Charles D. Schultz
Can We Make It Here Anymore?

There has been renewed discussion of the "Buy American" mandates recently. AGMA has a long history on this topic and successfully challenged -in court- the illegal "dumping" of imported gearboxes on our domestic market back in the 1980s. National policy, unfortunately, did not support that court decision and the retrenchment of American gear manufacturing began. Read more here:

Can We Make It Here Anymore? | (geartechnology.com)

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Michael Goldstein founded Gear Technology in 1984 and served as Publisher and Editor-in-Chief from 1984 through 2019. Thanks to his efforts, the Michael Goldstein Gear Technology Library, the largest collection of gear knowledge available anywhere, will remain a free and open resource for the gear industry. More than 36 years' worth of technical articles can be found online at *www.geartechnology.com*. Michael continues working with the magazine in a consulting role and can be reached via e-mail at *michael@geartechnology.com*.

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Mixed Bag

Publisher & Editor-in-Chief
Randy Stott

Every year at this time we put together our "State of the Gear industry" issue. As in years past, the centerpiece of the issue is our annual survey of gear industry professionals, where we ask detailed questions about the year that's just gone by and the one that's coming up.

As you can imagine, with the way 2020 went, we were not expecting large numbers of enthusiastically positive respondents. To be honest, we were thinking more along the lines of doom and gloom.

But once again, the gear industry has surprised us with its positive attitude and resilience. One of the questions we ask our respondents every year is their level of optimism regarding their companies' ability to compete over the next five years. Historically, the percentage of our industry indicating some level of optimism has been somewhere in the range of 85%. This year, that number was 76% — low from a historical perspective, but nowhere near as low as we expected. Most people still expect our industry to bounce back.

We do, too.

Of course, the survey numbers acknowledge the fact that 2020 was a really rough year. COVID hit the gear industry hard, like most other industriess. Plants were shut down. Workers were furloughed or laid off. People died.

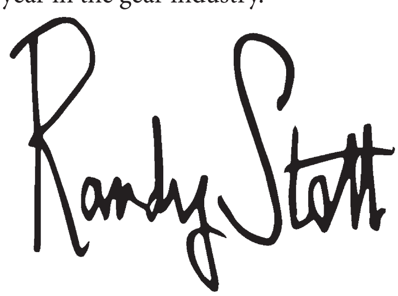
And although the pandemic has been devastating, the majority of our respondents expect 2021 to be better, with many indicating that they've already returned to normal operations and are expecting growth in sales and production over the next 12 months. And while it may take some time for employment and capital spending to come back, the majority are expecting these measures to at least hold steady – if not improve – in 2021.

On top of that, it's clear that many in our industry are looking toward the future, with electrification being the buzzword of the day. No other topic is as prevalent in the gear industry's thoughts — and this was *before* General Motors announced that its lineup of vehicles would be all-electric by 2035. Perhaps no other topic will have as much impact on our industry over the next decade — for better or worse. And while many are seeing opportunities in the growing number of electric vehicle manufacturers who are suddenly in the market for gears, as well as the need for much greater precision and higher performance gears, many others see the writing on the wall — which says that fewer and fewer gears will be required as vehicles become more electrified.

We hope you'll spend a few minutes reading through the survey results, not only to benchmark your own company and where you are in terms of the recovery, but also to gauge the overall mood of the industry and the thoughts of your peers. To make that easier, we've presented a lot more direct quotations from our survey respondents than usual. It's kind of like a giant bulletin board where everyone in the industry had the opportunity to post a note about what they were thinking in late January 2021.

The result is a mixed bag. Some of the comments will make you sad. Some will give you hope. Some are political, others technological. Individually each comment should be taken with a grain of salt. But when you look at the whole, there's insight there that can't be gotten from a chart or graph. Reading through them all, you get a sense of mood.

And overall — despite everything — the mood is hopeful. Let's make 2021 a great year in the gear industry.



AGMA is Here for You

John Cross, Chairman of the Board, AGMA

The annual Gear Technology State of the Gear Industry Report is always a must read for any industry leader. This type of study fits nicely into AGMA's overall mission, which includes providing business intelligence to the industry.

As Chair of AGMA, I had the opportunity to review the early tabulations, and wanted to share my perspectives on what jumped out to me. This is not an exhaustive overview but more of a reflection of what I thought was critical, and resonated based on my own 25-year industry career.

First — it is absolutely clear that everyone is starting to get onto the "electric drive is coming" train. Four years ago, AGMA's Board of Directors adopted a Strategic Plan that included monitoring the development of electric drive — we knew it was coming, but we were not sure when it was going to directly impact the gear industry, and for which applications. We saw it as an emerging technology.

With this study—and having hundreds of mentions — combined with what we are seeing in the consumer auto space — it is absolutely crystal clear that electric drive is moving from an emerging technology to an existing technology.

The key question is: How does this impact your company? And what response strategy should you have?

There are opportunities within the space — Noise, Vibration and Harshness will be a major focus, as companies attempt to electrify the power transmission. How can you support that shift? What engineering can you bring to the solution customers are looking for? Will the gear cutting operation move from the customer to the supplier base, and can you play a role?

Larger gear companies have already shifted their technology solutions from gears alone, to a more rounded out approach which includes fluid power as well as electric drive. Does your company have an opportunity to adjust its product portfolio? Should you do that organically, via internal investment? Or make a strategic acquisition?

These are now critical questions that gear companies involved in an industry being impacted by electric drive should be asking and developing plans to adjust and evolve.

To help support your efforts to answer these questions, I suggest you join AGMA — and become part of our Electric Drive subcommittee on Emerging Technology. This group now has 80 members participating in regular meetings to discuss the impact of electric drive on a variety of markets, and is going into depth on the technology behind each development, to ensure industry knows the ripple effects.

AGMA also tracks the Industrial Internet of Things, Additive Technology and New Alloys, and has subcommittees for each for your team to participate and keep up.

Joining the committee — which is for members only — gives your team an edge on the competition as you stay ahead of the developments that industry is clearly saying are coming, and impacting us in 2021 and beyond.

Second — training is a critical issue facing our industry, and when I say training — it is not just the simple act of training a person how to run a CNC machine — it includes finding a person willing to work for the company too! You must have people before you can train them.

We have all known that the aging workforce is an issue for us; we simply need to walk the shop floor to clearly see that our teams are getting older, and there are not as many younger faces coming into the industry.

And when we do find talent, they are often as green as green can be, and we need to spend months to get them up to speed on every aspect of manufacturing.

So the questions are simple; the response strategies are more complex.

What formal training regime do you have in place to take a brand-new employee from off the street, to either engineering a power transmission system in the office, or producing one on the shop floor?

What does your new employee do on the first week of work, the third month? The first year? How does their learning progress?

At AGMA, if you are a member — you have incredible FREE resources to support your new employees' first week. AGMA has developed, with the assistance of the AGMA Foundation, the free workforce training series, online training videos that provide a significant entry-level overview of gear engineering and production. At ASI, we require every new employee to devote 20 hours to go through the videos within the first two weeks.

After that, AGMA has more than 20 online or face-to-face classes that your teams can take to support every single facet of your operations. From design to gear failure, and all the steps between — AGMA has the best technical training available to the industry today, period. We added operator level classes in 2020, so we now support both your engineering teams and your shop teams.

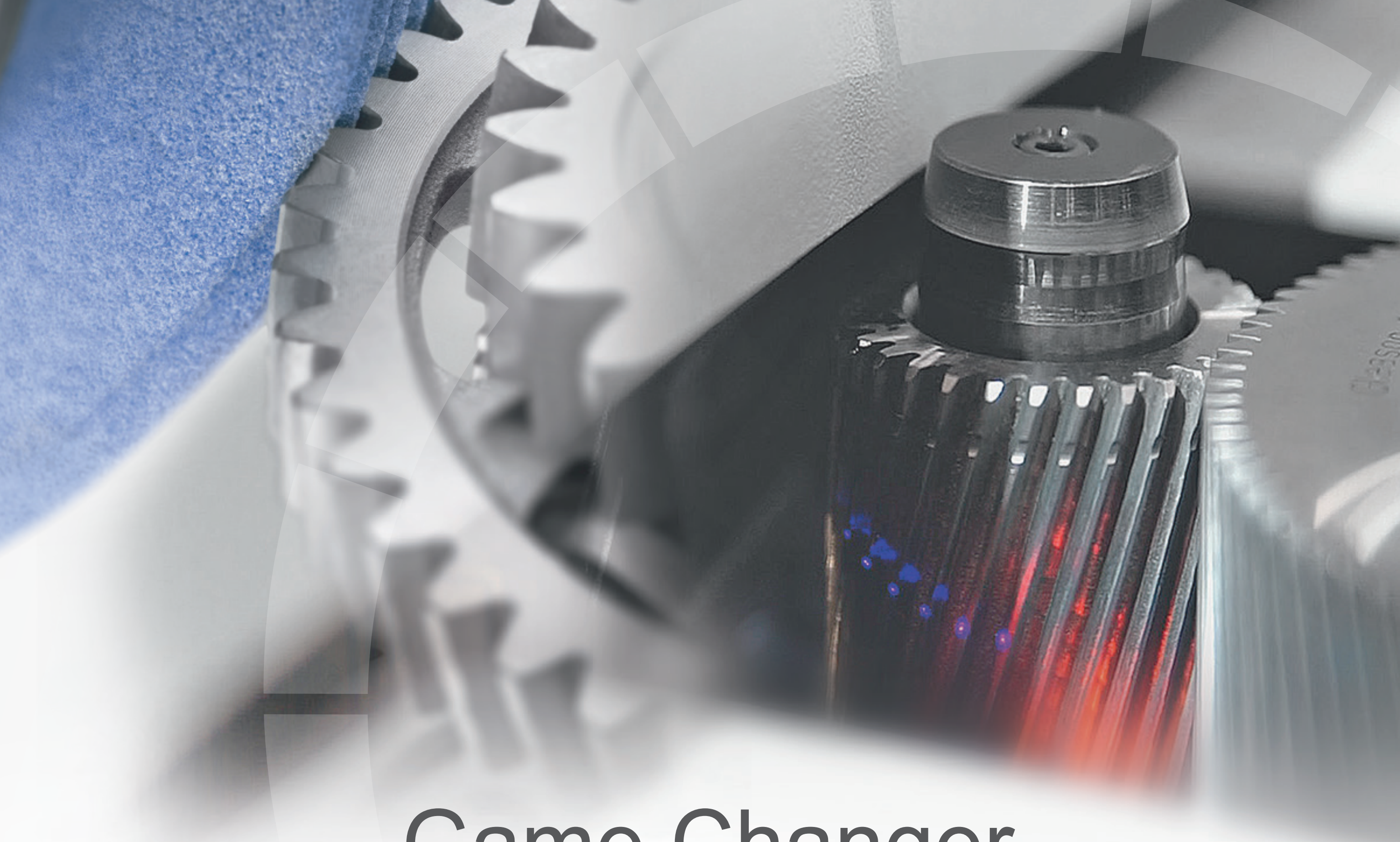
If you are an AGMA member, you can make the AGMA Education Classes a critical part of your formal training program. Why not contact the Education Team (education@agma.org) and get the class schedule on your calendar, and then make sure to send your team to the various classes as part of their growth and development strategy?

The year 2021 is going to be a challenging one — as the survey illustrates. COVID-19 continues to drag projects down, uncertainty abounds, and we have a new Administration impacting policies and trade. These trends with the two I outlined mean that your company should turn to AGMA now more than ever. We are spending time and effort to stay on top of trends impacting OUR industry, because we are working together to create the industry's future.

If you are a member, join our committees and be part of the team building the future.

If you aren't a member, join AGMA and get involved — it may be the best business decision you make.

John Cross
Chairman of the Board, AGMA
President and CTO, ASI Drives



Game Changer

With Gleason's new Hard Finishing Cell (HFC), fast, automated production of 100%-certified precision gears is a reality. HFC connects GX Series Threaded Wheel Grinding and the new GRSL Gear Rolling System with Laser Scanning in a Closed Loop; gear checking, analysis and correction are done in-process, in real time.

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Power Skiving - High Quality, Productivity and Cost Efficiency in Gear Cutting

DR. MANFRED BERGER, MAG – STEPHAN DOERR, HESSAPP – MARIO GRUEBERG, MODUL

Like electric mobility, the technology of power skiving has been known for more than 100 years (Ref. 1) and, with the availability of 5-axis machining centers, has found its way into individual and series production due to its convincing process flexibility. With e-mobility, a market is now growing which demands high precision (low running noise), high power transmission (torque and speed) from the product and equally high product flexibility in volume production. The use of planetary gears for reduction or as a differential in the drive system also increases the demand for internal gears. As with all manufacturing technologies, quality, cost optimization, flexibility and productivity are the top issues. "Power Skiving" makes a significant contribution to each of these aspects.

In addition to traditional gear machining processes such as hobbing, gear shaping and broaching, skiving is a continuous machining process for soft and hard machining of internal and external gears (Ref. 2). The skiving process is characterized by the tool and workpiece axes arranged in a certain relationship to each other: the axis cross angle (Fig. 1). With the coupled rotation of workpiece and tool, a relative movement of the cutting edge in the tooth space is thus created. By superimposing a feed motion, both add to the movements to the feed speed and guide the cutting edge along the workpiece axis. In this way the tooth space is "peeled out" of the workpiece in several cuts (Fig. 2). The cutting speed results from the rotational speeds of tool and workpiece in relation to the axis cross angle. Significant for the skiving process is the short machining time (approx. 30 to 50%) in comparison to the likewise flexible gear shaping and the ability to apply the gearing close to an interfering contour (workpiece shoulder). The smaller the axis cross angle, the closer towards the interference contour can be machined.

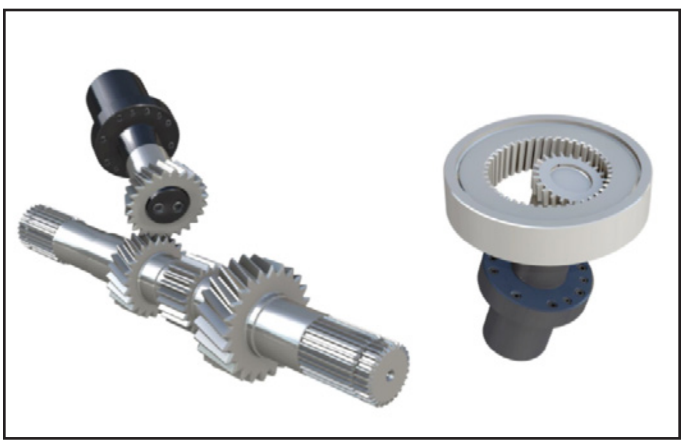


Figure 1: Gear skiving of internal and external gears with a relation of tool and workpiece axis arranged at an angle to each other.

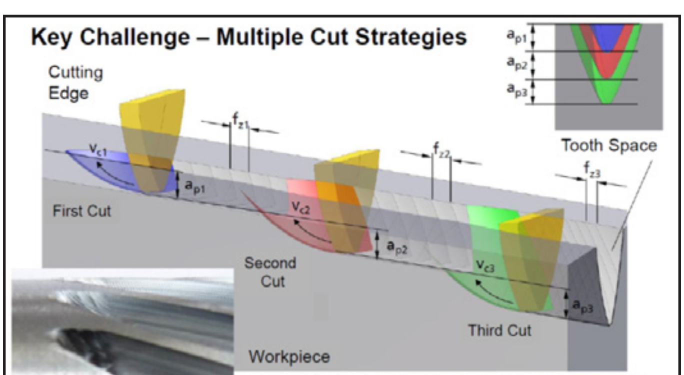


Figure 2: Production of the tooth space on the workpiece using the multi-cut strategy [3] and illustration of the kinematics with sickle-shaped chip formation when rotating the workpiece and tool with crossed axis arrangement (axis cross angle).

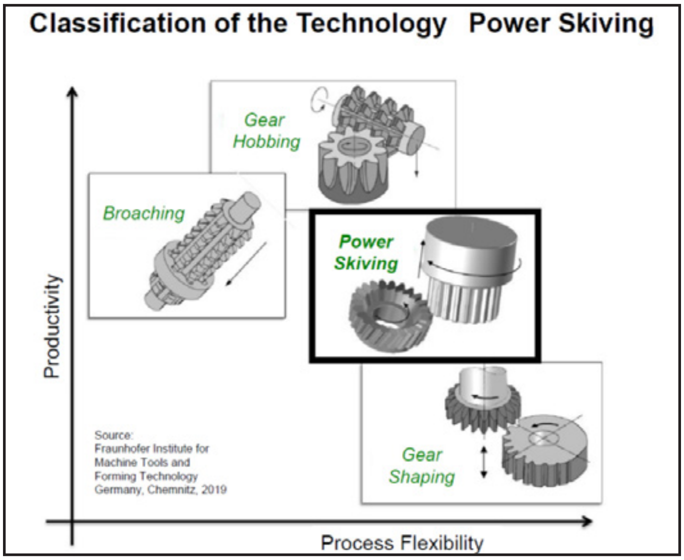
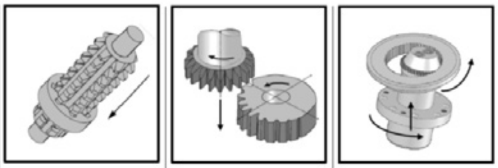


Figure 3: Power Skiving in comparison to other gear manufacturing processes.

While the traditional alternative processes for gear machining such as broaching, gear shaping and gear hobbing are mainly used in technology-specific special machines, gear skiving can be applied on special machines and on modern 5-axis machining centers. In recent years, skiving has made a quantum leap in industrial manufacturing with the availability of modern control technology for spindle synchronization, tool technology for high-performance cutting and a machine structure that meets the high demands for rigidity and dynamics.

The main advantage of the above-mentioned process integration is that the components can be finished without or at least with fewer downstream machines. This eliminates a large part of the loading and unloading of the components, the intermediate transportation and the quality losses due to clamping faults in the subsequent machining processes. The FFG Group therefore offers users the technology of Power Skiving on different machine concepts (Modul gear cutting machine skiving with alternative machining processes, Hessapp vertical turning



Source: Daimler AG Dr. Achim Raab April 2019	Broaching		Gear Shaping		Power Skiving	
Cycle Time [min]	0,65	↑	1,95	↑	1,0	→
Set-up Time [h]	1,5	↓	1,0	↓	0,5	↑
Layout Flexibility	height/below floor level	↓	crane hook MC	↑	crane hook MC	↑
Dry Machining/MQL	no	↓	partially possible	→	yes	↑
Cutting Tool Cost	300 %	↓	100 %	↑	130 %	→
Process Compensations	not possible	↓	related tot Df/MdK	↓	with compensations	↑
Investment	120 – 150 %	↓	100 %	→	100 %	→
Summary	↓		→		↑	

Figure 4: Evaluation matrix of gear machining in series production [5].

machine for disc-type components with swiveling workpiece axis or the Boehringer shaft turning centers with optional tool spindle). In an isolated comparison of the machining scope for gear cutting, Power Skiving can keep up with broaching and gear shaping and only has to admit defeat to classical gear hobbing in terms of economy. However, for series production on a greenfield site, costs, quality and productivity must be assessed as a whole, and the evaluation matrix for Power Skiving can be even more advantageous (Fig. 4).

Advantages of Power Skiving:

- Elimination of the loss of accuracy with multiple clamping in subsequent operations (quality improvement) - turning (as well as other operations) and gear cutting in one clamping
- Floor space-saving process due to less logistics space for subsequent machining
- Lower total investment (no special foundations (broaching), periphery, operating and maintenance costs in the system)
- Economical machining due to short machining times (compared to gear shaping)
- Process flexibility (process optimization, retooling, path compensation, tools, cutting materials)
- Dry machining possible, no need for cooling lubricant or oil (environment, costs)
- Product flexibility (quick changeover to other workpiece types, gear profiles, straight and helical gearing)
- Production of gears close to interfering contours (shaft shoulder)
- Internal and external gearing
- Soft and hard machining - Roughing and finishing
- Hardening distortions can be compensated by tool path corrections
- Broad competence of machine and tool suppliers

The obvious advantage of "Power Skiving" can be found in process integration. This background also explains the FFG Group's multiple path approach to machine development. Both machines for "Power Skiving" offer additional machining technologies such as turning, drilling and milling in addition to the gear skiving process. In the process combination, a workpiece can be almost completely machined on the machines. With the "Power Skiving" option on the Hessapp DVH 500, which is very well established in the market, we approach those customers that have to apply a gear to the turned part. With the Modul VS 250, the focus is on the classic manufacturer of gears and transmissions.

A special software package for technology and process development, for simulations and for process visualization is available for both machines. FFG's skiving software is compatible with the *SkiveAll* design and simulation software from IWU Chemnitz, an institute of the Fraunhofer Gesellschaft (Refs. 6, 7).

SkiveAll contains algorithms for the optimization of component quality. A kinematic process model is created from the workpiece analysis and the required tool geometry is calculated. In order to fully exploit the potential of skiving, this digital process twin also takes into account the machining forces, tool wear and stress on the processing machine (Fig. 5). The process (cutting sequence, cutting values, machine settings and other data) is exported to the machine where it serves as the basis for the automatic generation of the NC machining programs.

When coupled with a measuring machine, the data is

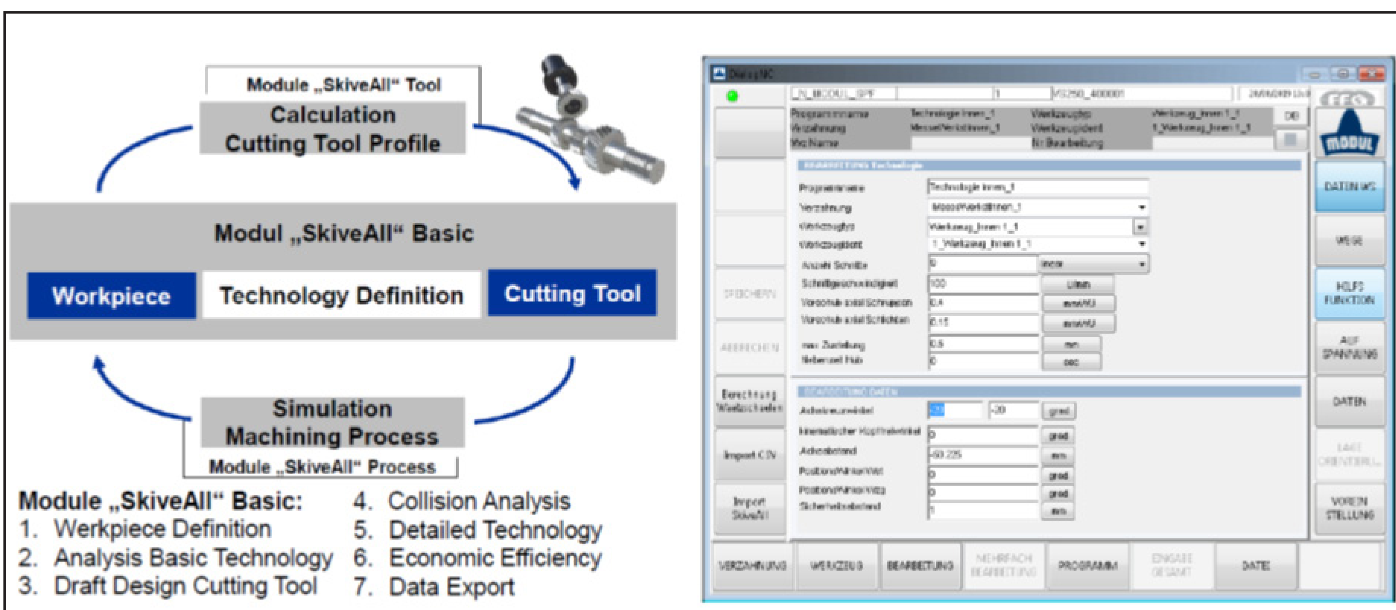


Figure 5: Application software for designing gear skiving processes SkiveAll (left) and input mask of the machine control DialogNC (right; operation, workshop programming, NC program generation, import/export to peripherical units) with direct coupling of both systems.

transferred in GDE format (Gear Data Exchange, Ref. 8) or in customer-specific formats. This allows a closed process chain to be established from the workpiece drawing to the finished product. "Closed Loop Manufacturing" (Ref. 9) is becoming a key issue for gear machining in order to further strengthen its position compared to the gear cutting processes of gear shaping, broaching and hobbing, which have been continuously developed for decades.

Another component is the Modul Tool Manager, a sophisticated tool management system that has already been supplied with gear hobbing machines.

For services, FFG offers an outstanding support through the digital maintenance manual installed on the machine, which provides maintenance and repair instructions in words and pictures directly at the machine. The display of maintenance intervals or the preventive announcement of due maintenance is just as possible as the logging of completed tasks. All service data can be uploaded and evaluated externally.

The gear skiving machine Modul VS 250 complements the successful product range of gear hobbing machines with the "Power Skiving" technology (Fig. 6). The process and production advantages described above are primarily aimed at suppliers and production plants in the automotive industry, regardless of the drive concept with combustion engine or e-drive. However, the machine with its tool magazine is also suitable for more complex workpiece assortments in small and medium volume production.

The 30 kW main spindle of the VS 250 allows a tool speed of 8,000 rpm, the workpiece spindle offers a maximum speed of 4,000 rpm. The tool magazine, already included in the basic equipment, has 6 pockets for tools with an HSK 100 interface.

Figure 6: Gear skiving machine MODUL VS 250 with automation and view into the work area.

Figure 7: Vertical turning center HESSAPP DVH 500 L WS for „Power Skiving" with integrated automation and part supply via conveyor belt.

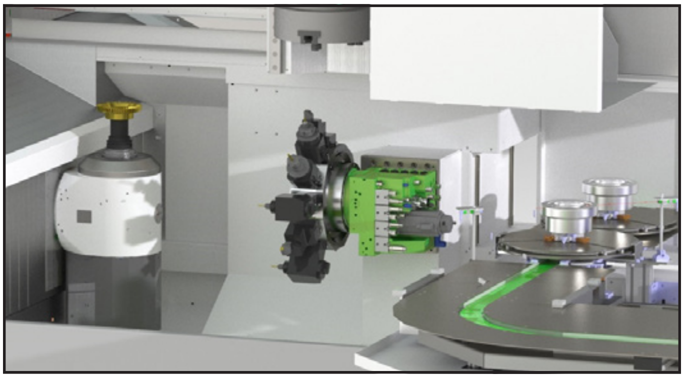


Figure 8: Work area of the CNC turning machining center HESSAPP DVH 500 L WS - view into the work area (suspended workpiece spindle, swiveling tool spindle, tool turret with a.o. driven tools - direct loading/uloading with the workpiece spindle (pick-up).

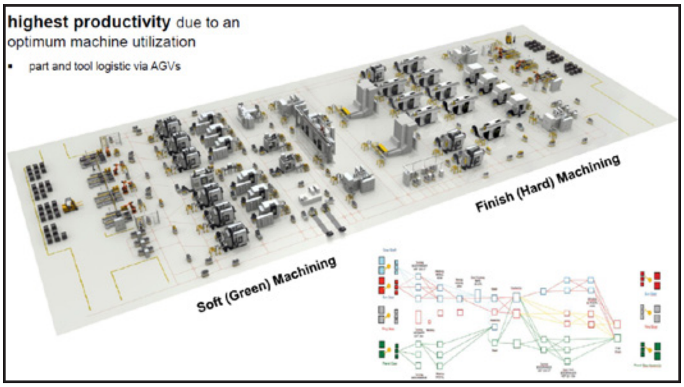


Figure 9: Algorithmic production system [10] for components of a planetary gear with flexible configurable material transportation by floor vehicles (example of a turn-key system for the complete machining of wheels and shafts).

- Maximum producible module m=6
- Maximum workpiece diameter=250 mm
- Automation through integrated loading gantry or external robot
- Possibility of mirrored design for integration into existing production lines or when replacing existing machines

The vertical Pick-up Turning Machining Center DVH 500 L WS (Fig. 7) can pick up and completely machine workpieces up to a swing diameter including clamping elements of 500 mm. For this purpose, driven tools can also be accommodated in the tool turret, which is equipped with state-of-the-art process monitoring (*MONTRONIX*). To increase the machine dynamics, the X-axis can be equipped with linear drives on request. In addition to the classic machining operations of turning, drilling, milling and grinding, the "Power Skiving" option package now also provides an additional swiveling tool spindle (Fig. 8) with a torque of 270 nm, a maximum speed of 7,800 rpm and an HSK 100 tool interface:

- Maximum producible module m=6
- Integrated workpiece handling from the conveyor belt with the pick-up spindle
- Optimum set-up operation
- Modern special software for workshop programming and process visualization SkiveAll with dialogue programming
- Main spindle with max. 4,000 rpm and 795 nm @ 40 %
- Y- axis stroke ±300mm
- Advantage of manufacturing an internal gear for workpieces with an internal shoulder

Both machine types can be integrated into existing production lines for wheels and shafts as a replacement or supplementary investment or can be used in FFG's turnkey plants with full effectiveness of the potential of multi-process technology. The Algorithmic Production System (Fig. 9) is particularly suitable for gear production, where not the individual component but components in containers (lots) are transported to the subsequent processing section, offering the best productivity and resulting lowest unit costs. These production systems are characterized by the fact that process-specific machine groups are planned in the system, which are approached with different components depending on capacity utilization and availability. It is therefore essential that the individual machines are designed for the acceptance of different components in volume production and this process flexibility requires the coverage of the largest possible machining scope (e.g.: turning, milling, drilling and gear cutting) in one clamping. The logistics target for an order (container/batch) is determined based on the respective current capacity utilization of the production cells and thus the available production and peripheral machines are optimally utilized. Both machine types for skiving can also be optimally integrated into conventional multi-stage production plants and agile manufacturing systems (Ref. 11).

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Helios

ANNOUNCES STRATEGIC APPROACH TO LARGE-GEAR DEBURRING

Chamfer-deburring of large gears — considered here to be those over 1-meter diameter — demand significant labor that comes with the risk of inconsistency and low quality. In partnership with Tecnomacchine, Helios announces an improvement to such applications. "For very large spur and helical gears, this deburring approach cost-effectively reduces labor and increases consistency and quality," said Adam Gimpert, president of Helios Gear Products.

For such large gears, several challenges demand improved solutions. Because these gears take significant time to move and fixture, a dedicated machine for deburring such workpieces becomes impractical. This is due to complex setups and relatively expensive machine components, such as precision motors, electronics, and structural elements. To solve these challenges, Tecnomacchine has developed a solution that adds chamfer-deburring capability to a manufacturer's existing finishing equipment, either hobbing or grinding. The key benefit to this "deburring unit" is that the workpiece remains fixtured from the prior finishing operation, and the same platform rotates the workpiece for the chamfer-deburring operation.

This added capability comes in a simple package for less than half of the cost of a dedicated machine. The deburring unit either mounts permanently to the existing hobbing/grinding machine structure or it uses a clamping system to temporarily mount for operation. Once the unit is positioned, the hobbing/grinding machine rotates the workpiece, and the deburring unit

engages a disk-type cutter to shear away large burrs particularly at the root of the tooth. This allows consistent, high quality chamfer-deburring in subsequent steps. Next, the unit simultaneously engages two tools to deburr bottom and top of the gear.

Manufacturers with large-gear finishing machinery, such as hobbing or grinding equipment, will welcome this strategic approach. Effectively, this solution simply adds to existing machinery new chamfer-deburring capability as a subsequent cycle without the need for re-fixturing. Consequently, manufacturers can have a simple, productive means for reliable, high-quality gear chamfer-deburring.

Heliosgearproducts.com

Chiron

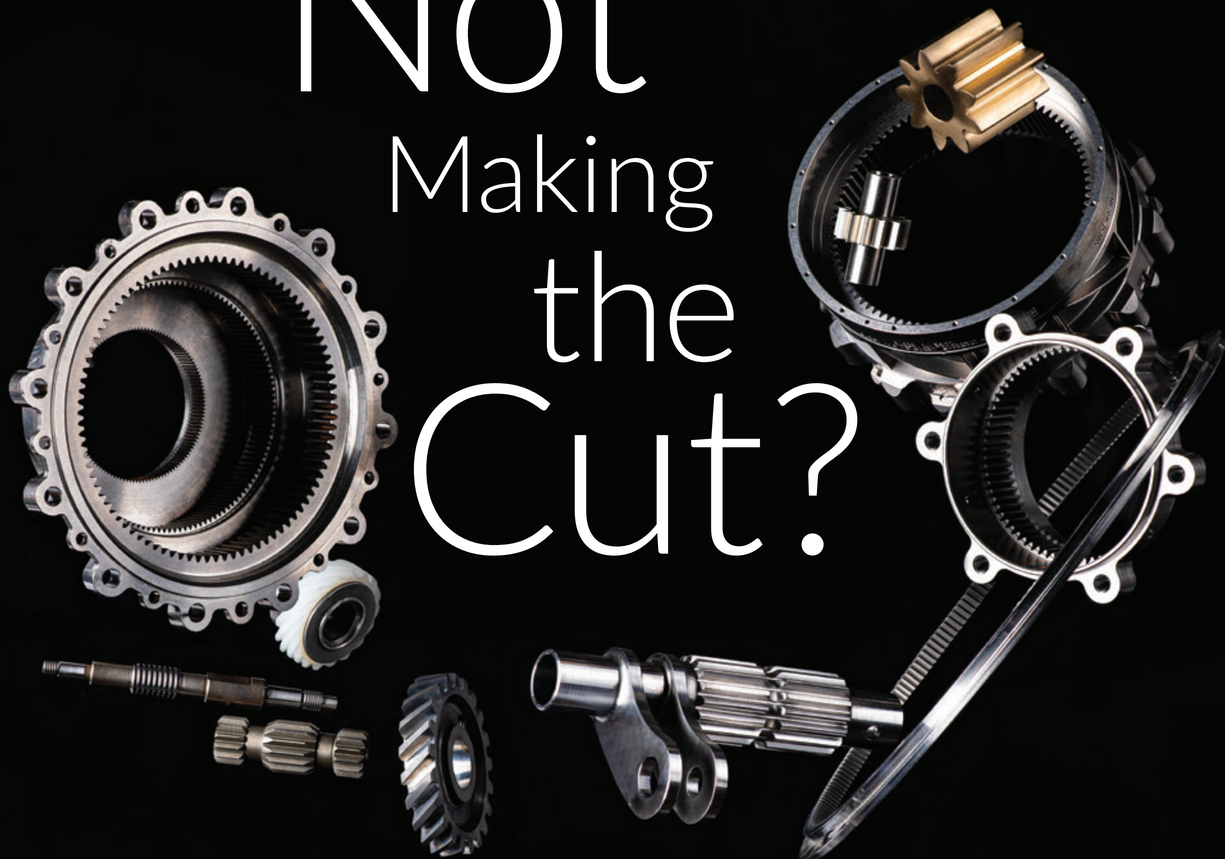
INTRODUCES 5-AXIS, TWIN SPINDLE MACHINING CENTER

The new twin-spindle series DZ 22, with spindle clearance of 600 mm, is designed to completely and rapidly machine complex, large workpieces, including housings for electric motors and transmissions, oil pumps, chassis components, and more. Chiron introduced the DZ 22 W five axis at its virtual open house in May. The company also offers a 4-axis variant of the Series 22.

According to the company, the Series 22 combines both high-speed and high-precision processing for complete production of even large high-precision components. Featuring two workpiece-changing table variants, part capacities are generous - the 4-axis trunnion plate version handles 680 mm × 1,330 mm dia., up to 600 kg; and the twin-spindle 5-axis version handles 2 × 599 mm × 340 mm dia., up to 150 kg.

Key to success of the small-footprint innovative machine concept is a machine platform using a moving gantry design. The rigid machine bed and active component cooling enable the required degree of precision on the workpiece. High acceleration — X-Y-Z max. 10–10–17 m/s² — in all axes and rapid response to programming inputs ensure dynamic machining as never before seen with workpiece dimensions of this size range. Axis travel distances are X-Y-Z max. 620–650–600 mm and rapid traverse speeds X-Y-Z max. up to 120–120–90 m/min.

In addition to precision and dynamics, Series 22 also offers impressive flexibility. From very complex workpieces or product series with many different tools: The magazines offer space for up to 77 tools and, thanks to the integrated workpiece changer, the workpieces are loaded and unloaded during machining, saving cycle time. Tool change time from 3.1 sec., chip-to-chip.


Not
Making
the
Cut?

Spindle options — one fast, one strong

Depending on the processing task, two different main spindles are used in Series 22: a fast spindle with a speed of up to 20,000 rpm and a torque of up to 137 nm for workpieces made of aluminum or aluminum alloys. Or a strong spindle with a speed of up to 12,500 rpm and a maximum torque of 200 nm for hard materials and large tools. The 22 series is also available as an HSK-A100 machine for further stability and performance.

Simple, clear access

The working area is easily accessible, and the process easy to see through large glazed doors. The control panel is located directly next to the working area, making set-up easier. The new machines are operated easily and according to context via the Chiron TouchLine operating system.

On the back, the tools are inserted in the chain magazine, and the tool data can be entered here directly via the operating console. Tool replacement is carried out during machine operation; the new tool is clicked into the magazine with a single movement of the hand.

Modular design, application-oriented

Series 22 is available with a ball screw drive or a linear direct drive. You can also choose from two plate variants: A suspension plate for four-axis machining or two face plates for five-axis simultaneous machining. All models can also be equipped according to the application with a cooling system, suction unit, chip conveyor, individual tool packages and more.

To maximize uptime, Chiron develops individual automation solutions with the customer. The solutions range from robot loaders to pallet handling systems.

Even better with Chiron SmartLine

To tap the full potential of digitalized production, Series 22 is prepared for the integration of various SmartLine modules to optimize productivity, product quality, and machine availability.

ConditionLine: Early detection of non-typical operating behavior and targeted planning of maintenance and repair

ProcessLine and ProtectLine: Reliable protection against machine crashes with a digital twin, both in preparation and during running operation. The machine operator is only shown those functions that are useful in the particular operating situation. TouchLine also offers enormous expansion possibilities, and Chiron is working on many features that will help customers exploit the potential of highly productive machining centers.

Optimized machine assembly and logistics processes for shorter delivery times

The machining centers are built in the new Chiron Precision Factory in Neuhausen, Germany, and are characterized by maximum precision and faster availability. The machines are produced in a cluster assembly process — one team, one machine — in shorter cycles. For each order, the optimized processing saves about two to three weeks of time, so that customers can get started with production sooner. And better too, thanks to advance simulation of processes: All machining which is later carried out on the machine can be programmed, simulated and optimized right in the Chiron Precision Factory.

"To assemble a machining center that combines maximum productivity with the highest precision, you need a factory that is ideally suited to it. The design and construction of the Chiron Precision Factory therefore went hand in hand with the development of our new 16 and 22 series machines. The primary goal was to create an optimal assembly environment for the state-of-the-art machining centers right from the beginning. We were able to optimally plan and implement material flow, temperature control, cranes and much more," said Bernd Honold, project manager operational excellence at Chiron.

www.chironamerica.com

C-B Gear & Machine

EXPANDS CAPABILITY WITH 5-AXIS MILLING

C-B Gear & Machine has expanded its precision milling capability with the addition of a new DMG MORI DMU 210P2 5-axis milling center.

The DMU 210P2 is one of a handful of five-axis milling machines in North America that can perform complex milling operations as well as mill gear teeth, making it state of the art machine technology. Reduction in set up and run times give C-B Gear a new capability for the high-speed production of any gear type on the market up to AGMA quality class 12 and higher. Cylindrical and right angle gearing up to 82" in diameter, soft or hard finished are possible.

Additionally, C-B Gear can now produce hard finished spiral bevel gears to either Gleason or Klingelnberg tooth forms. The DMU 210P2 adds to the company's wide range of large precision gear manufacturing, which complements C-B Gear's tooth grinding capability up to 4 meters in diameter. C-B Gear is one of the few gear manufacturing facilities in the country with this type of capability in this size range.

"We're excited about the prospect of expanding into new markets with this type of capability" said C-B Gear General Manager, Frank Irey. "We've added all of the bells and whistles that help C-B Gear become even more competitive in the industry with on-board tooth inspection, tool offset compensation and automatic workpiece eccentric adjustments. Customers can expect higher quality and faster turn-around times than in the past".

Since 1952, third-generation family-owned C-B Gear has been providing a wide variety of industries with quality products at a competitive price. "Expertise in precision mechanical component production, gear manufacturing and aftermarket gearbox repair has established C-B Gear as a highly valued supplier to our customers," said Irey.

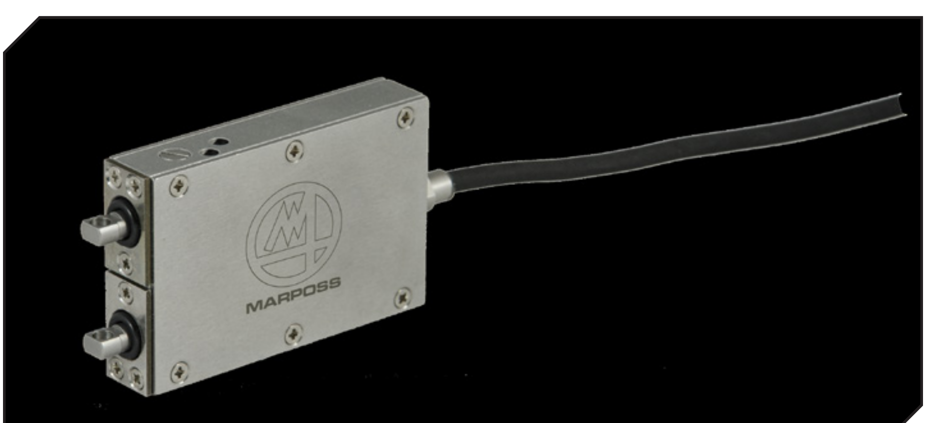
www.cbgear.com

Marposs

OFFERS MINIMICROMAR3 GAUGE FOR SMALL GROUND COMPONENTS

Marposs has announced Minimicromar3, an in- and post-process grinding gauge designed for small diameter measurement. This ultra-compact gauge is well-suited for the manufacturing of very small ground components such as fuel injectors, electronics and other parts.

The Minimicromar3 is designed for measuring external diameters, positioning and length for both smooth and interrupted surfaces. It can measure workpieces from 25 mm to 42.5 mm with a measuring range of ±100 μm and a repeatability of ≤0.1 μm. It is designed with a high degree of protection against coolant and abrasive substances. Its low thermal drift value (<0.1 μm/°C) helps maintain high measurement precision.



The Minimicromar3 can be used with a range of Marposs electronic units including the P7ME, P7UP, P7SYS, Blù and Blù LT for higher end applications and the P1dME and P3dME for entry to mid-level applications. The gauge, together with the associated electronic control unit, exchanges information and signals with the machine in order maximize performance and achieve the desired results. It is designed for quick and easy installation and operation.

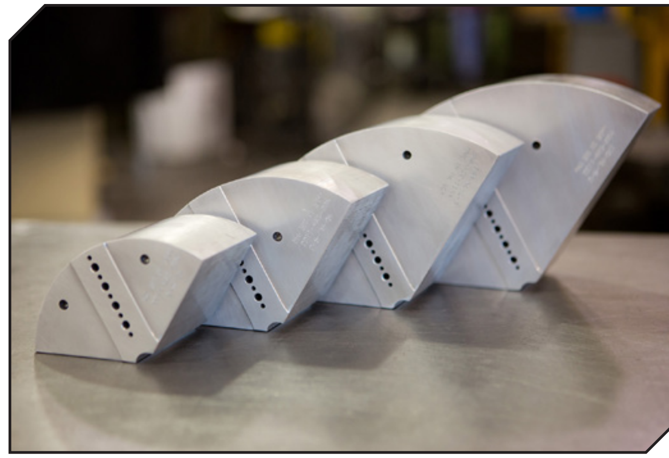
www.marposs.com

Dillon Manufacturing

OFFERS PIN LOCATION JAWS FOR AIR CHUCKS

Dillon Manufacturing, Inc. full grip (pie) blank jaws manufactured for Northfield, Microcentric and others, are CNC milled to provide maximum accuracy for workpiece location, enabling air chucks to hold thin wall and deformation sensitive workpieces firmly. The full grip jaws are manufactured for chuck sizes ranges between 4” and 10” diameters.

Full grip jaws are available in 1018 steel and 6061 aluminum. Jaw heights are available between 1’ and 4". Jaws can be customized per customer request — a quotation of these engineering services are performed at no charge by experienced Dillon application engineers.



They are typically available with industry-leading lead-times of 3 days or less.

www.dillonmfg.com

Schunk

STATIONARY WORKPIECE CLAMPING SOLUTION PROVIDES AUTOMATION UPGRADE

With its lean automation program and the Plug & Work portfolio for cobots, Schunk already offers cost effective solutions for component handling. Now the competence leader for gripping systems and clamping technology expands its offering for stationary workpiece clamping by launching a low maintenance vise that makes it easy to transition into the world of automation.

The pneumatically actuated clamping force block Schunk Tandem PGS3-LH 100 can be directly mounted via the integrated flange on the machine tables, dividing heads or Schunk Vero-S NSL3 150 clamping stations of machining centers. Its compact and square design ensures optimum accessibility and

enables a considerable stroke of 6 mm per jaw.

With a clamping force of 4,500 N and a repeat accuracy of 0.02 mm, the low-maintenance Schunk Tandem PGS3 is suitable for basic applications in the field of aluminum and plastics machining. Special quality features include a chip-repelling design, the surface-treated components in the power flux, and the fact that the long base jaw guidances avoid a lifting up of the chuck jaws. The vise can be equipped with all standard top jaws with tongue and groove (KTR, KTR-H) from Schunk's extensive chuck jaw program. The vise can be immediately incorporated into any machine tool: it has lateral air connections and built-in keyways.

Schunk.com

Forest City Gear

EXPANDS THREADED WHEEL GRINDING CAPABILITIES

Forest City Gear now can perform hard fine finishing of larger diameter cylindrical gears faster and more efficiently in higher volumes with the addition of a new Reishauer RZ 410 Threaded Wheel Grinding Machine.

The new Reishauer uses the threaded wheel (continuous generating) grinding process to combine very high metal removal rates and short idle times to produce gears as large as 500 mm in diameter and module 10 and shafts up to 700 mm in length much faster and more efficiently than profile grinding.

For smaller lot sizes, specialized, and prototype work the Reishauer also gives Forest City Gear the ability to perform profile grinding using either CBN plated or dressable grinding wheels that can be modified on the machine with an on-board CNC dressing unit, working in conjunction with integrated inspection.

The unique architecture of the Reishauer also provides optimum speed and accessibility during wheel or workpiece changeover. The turret-mounted grinding spindle can be rotated between grinding position, dressing position and an easily accessible wheel-changing position that allows the operator to change the clamping fixture at the same time the grinding wheel is being dressed on the opposite side of the column.

The capability of this machine to perform threaded wheel grinding, profile grinding, and polish grinding to create gears with 'mirror' finishes, along with the ability to control bias, allows it to fit perfectly within Forest City Gear's very diverse product requirements, according to Forest City Gear Technology Manager Gene Fann.

"The Reishauer adds speed and capacity for production of larger gears at lower cost per piece to our grinding operation, with the versatility to accommodate a very wide variety of customer requirements, whether the high precision of a one-off master gear or ultra-quiet gears with mirror finishes produced in higher volumes," said Fann. "With quality and delivery standards never higher in all the industries we serve, this machine is a great addition."

www.forestcitygear.com

Pittler SkiveLine

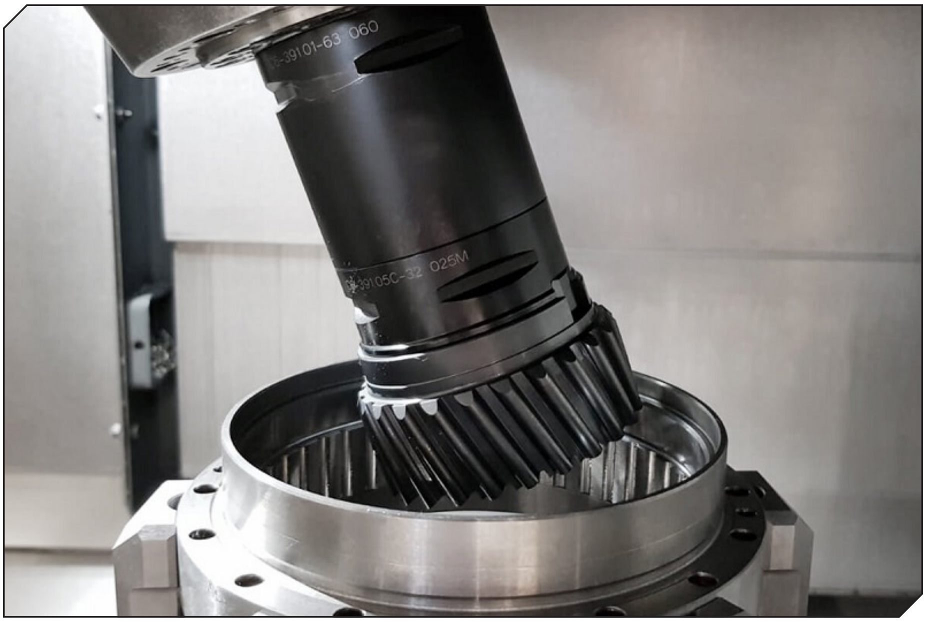
INCREASES QUALITY WHILE REDUCING COSTS

The future of automation lies above all in the intelligent combination of the respective strengths of man and machine. In order to achieve better results, conventional procedures and processes are being rethought from the ground up. In industrial production, this is primarily a matter of improved ergonomics with a simultaneous reduction in manual processes. As a result of this development, robotics has grown by an average of more than 10% in recent years. An end to this growth is not in sight for the time being - robots are a key component in the automation of production processes.

Robots place extreme demands on positioning accuracy with high dynamics. For this reason, low backlash gears with high torsional stiffness are used in the development of drives for jointed-arm robots. However, this requires a correspondingly high-quality production technology for these gears. Robot gearboxes have a high transmission ratio and a compact design. Planetary, shaft and cycloidal gearboxes are used as robot gearboxes, as well as new gearbox solutions such as the Galaxie from Wittenstein. Cycloidal gearboxes currently account for the largest market share in Asia. The high transmission accuracy requires a limitation of tolerances, so that the gear profiles, the pitch accuracy and the position accuracy must meet increased requirements. Even small deviations in the tooth width or minor positional deviations lead to variations in the rigidity of the drive. Due to the unfavorable size ratios, the robot's compliance at the tool tip is many times greater than the play in the gear.

In cycloidal gears, the challenge is to machine the gear teeth in relation to the cam bores. Here, tight tolerances must be maintained in order to achieve a minimum backlash. On conventional gear cutting machines, the gears are machined independently of the cam bores. Here the position orientation must be ensured by the clamping device.

The machining strategy, which is realized on a Pittler SkiveLine, follows a different approach. By machining the toothing and the cam bore in one clamping, the clamping device for machining a cycloid disc can be designed more simply without negatively influencing the form and position quality. The advantage of complete machining in one clamping is that the reference of the cam bore and gear teeth can be generated and corrected via the machine. This machining strategy even leads to a further improvement of the position quality. In this way, the Pittler SkiveLine contributes to solving an apparent conflict of objectives - to reduce manufacturing costs with improved quality.



In addition to external gearings, internally toothed housings can also be completely machined on a Pittler SkiveLine. This is possible by creating the special profiles with Pittler Skiving and machining all other functional surfaces by turning, drilling, and milling. The machining of components for robot gears on a Pittler SkiveLine is not limited to the green machining itself. To achieve the highest quality, the already toothed and hardened components can be finely machined. Here Pittler can fall back on the modular technology of the DVS Group.

The Pittler SkiveLine thus proves once again that no special machines are required for the manufacture of high-precision gearings, but that the key to success lies in the flexible and scalable basis of the DVS modular technology system. For this purpose, machining center, clamping and tool technology must be coordinated.

www.dvs-now.com

Drivetrain Hub

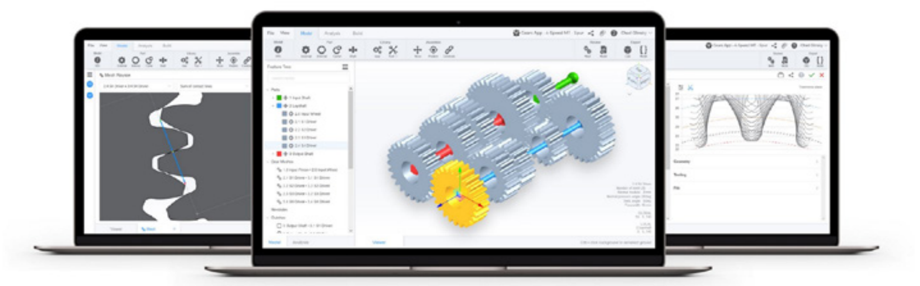
LAUNCHES GEARS APP

Drivetrain Hub has launched its fully web-based gear software, Gears App.

Gears App is the only Software-as-a-Service (SaaS) gear development platform that integrates gear system modeling, design-for-manufacturing, industry standards, powerflow analyses, CAD, FE, 3D printing, manufacturing, data management, and collaboration tools. Model, analyze, and build gear systems for parallel-axis and planetary architectures.

Gears App is accessible online from anywhere on any operating system, no special hardware, software, or complicated license required. It is the only professional gear engineering software made available as an affordable monthly subscription service, entirely online. Just open your web browser and start using it.

Drivetrainhub.com/gears



SMW Autoblok

OFFERS ZEROACT SYSTEM FOR MANUAL AND ELECTRIC ACTUATION

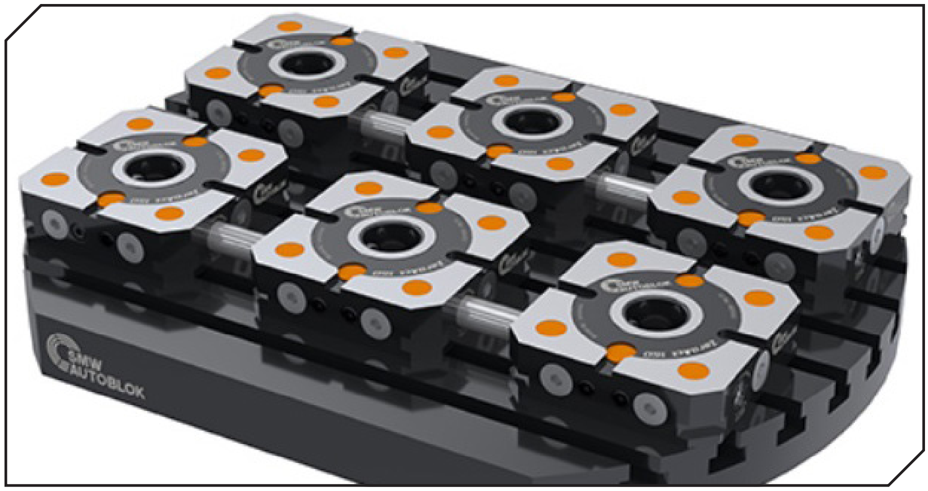
SMW Autoblok introduces the connectable ZeroAct workpiece positioning system ideal for manual and electric zero-point clamping used in a variety of machining applications including milling, inspection, and finishing operations.

With an ultra-low profile of 40 mm, ZeroAct is ideal for any zero-point application especially those where the z-axis travel of the spindle is critical. The ZeroAct features rapid open and closing of the modules and simultaneous actuation with one simple twist of the wrist generating 15kN clamp force. Easily actuate workpieces onto a table or adapter with a low stack-up of 38.1 mm, greatly increasing the z-axis travel.

The modular ZeroAct system, with a compact size of 150 x 150 mm, offers the ability to easily attach up to three clamping modules in a row with a connecting pin that is available in sizes from 5 mm to 105 mm. By actuating the first unit, all three units clamp simultaneously therefore it is not required to lock each unit individually into position like others on the market. This benefit adds tremendous flexibility to machine operations, saves time and increases operator safety.

The ZeroAct is also available in an electric e-motion version, unique to the industry, to fully automate the manufacturing processes. Using 24V power supply that operates with a built-in electro-motor, this system offers great flexibility to machining processes. Switch between a manual and electric ZeroAct version for fully automating load and unload processes. Pull down pins are fully interchangeable with the manually operated ZeroAct and other APS/WPS zero-point systems.

All modules are proofline sealed protected against corrosion and feature a built-in air cleaning function to ensure that the clamping system's support surface remains clean and free of chips during changeover or automation, greatly reducing maintenance and production time, and providing a repeat accuracy of <0.005 mm.



ZeroAct is part of the comprehensive lineup of stationary workholding systems that include the manual and pneumatic WPS/APS clamping modules, fully customized and self-centering vises that fully integrate with automation and pallet systems, and SinterGrip clamping inserts for ultra-low clamping depth and no pre-marking of parts. Systems provide high repeatability, maximum holding forces, and up to a 90 percent reduction in setup time.

www.smwautoblok.com

Siemens Digital Industries Software

INTRODUCES QUALITY MANAGEMENT SOLUTIONS

Siemens Digital Industries Software announces *Teamcenter Quality* software, a new suite of solutions that provide a closed-loop approach for quality management, from design to manufacturing on the shop floor and back again. *Teamcenter Quality* helps keep product development, quality planning and continuous improvement processes in synchronization to help maximize the value of change management and configuration management capabilities on the Teamcenter collaboration platform.

"Given today's product complexities and time to market agility needs, leading manufacturers include quality management into their collaboration, change management and data backbone, such as Teamcenter represents today," said Matthew Littlefield, president and principal analyst at industrial transformation analyst firm, LNS Research.

In today's market, companies are continuously challenged to reduce product and operating costs, while still improving quality, to distinguish products and gain a competitive advantage. Every effort must be made to improve efficiencies among teams that may be distributed across the globe. On the other hand, consumers are requesting more innovation, faster delivery and cheaper products to the market, while still ensuring their quality and safety. This new extension to the Teamcenter portfolio allows engineers to set quality requirements early in the design process and establish the parameters required to help ensure the product realized during the production phase will meet the necessary quality standards.

www.sw.siemens.com

Gear Factory of the Future

Edited by Matthew Jaster, Senior Editor

What does the future hold for the global gear industry? We're asking these questions regularly in the pages of *Gear Technology*. Electric drivetrains, advanced optical metrology, an increase in automation and robotic capabilities, 3D printing, and the Industrial Internet of Things (IIoT) will continue to change the look and feel of the shop floor.

The following three articles from Klingelnberg, GAM Gear and Gleason examine many of the changes taking place in gear manufacturing today.

Klingelnberg

Advances Optical Metrology with Sensors and Data Acquisition

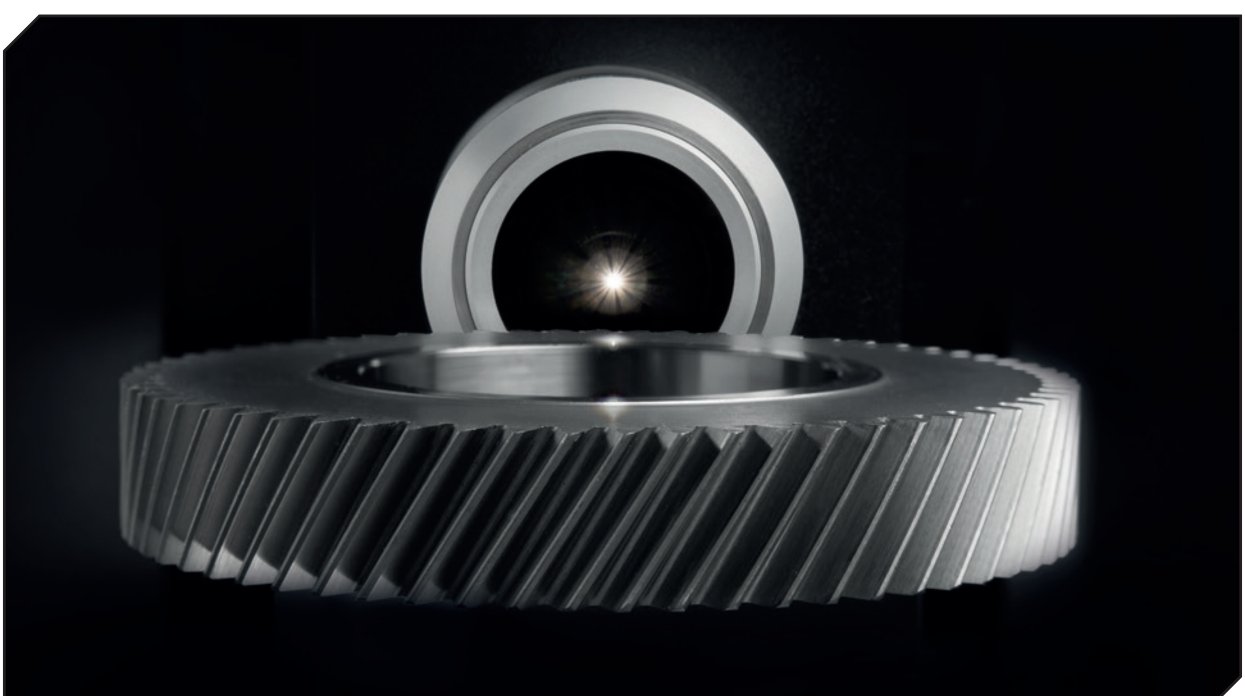
Klingelnberg first presented the initial development stage of the hybrid solution with optical metrology at the EMO Hannover exhibition back in 2017. The application at that time centered on digitization of axially symmetrical gear components. Components such as bevel gears and cylindrical gears, and other geometries as well, can thus be measured with an extremely high point density (digitized), followed by additional processing. This additional processing is extremely flexible. In addition to simply depicting the results as a 3D model, comparisons can be made against a CAD target geometry, or a geometrical evaluation can be conducted by creating sectional views. This application is used for reverse engineering, for example.

In the last three years, Klingelnberg has significantly advanced their Optical Metrology system. Particularly in terms of sensor systems, measured data acquisition, and further processing, there has been significant progress.

Figure 1 **Pitch Measurement with HISPEED OPTOSCAN.**

High Accuracy in the Sub-Micrometer Range

In the first development stage, a high-precision laser triangulation sensor was used. This sensor technology is well suited to the digitization application described above. However, physical limits in laser triangulation restrict its use for measurements in the sub-micrometer range on gear components. Because tactile gear metrology on the precision measuring centers over the years has achieved an extremely high level of maturity and thus also an impressive measuring accuracy, customers' expectations for optical metrology on a Klingelnberg measuring machine are correspondingly high. A restriction in accuracy that is accepted for digitization is not acceptable for other measurement tasks.



New White Light Measurement System

For this reason, Klingelnberg has been focusing its efforts on the entire signal chain in optical metrology and has joined forces with other development partners to develop a white light measurement system tailored specifically to the requirements of gear measurement. In this system, the active, current-carrying elements, such as a high-power light source, electronics and signal processing, are arranged separately from the sensor in the control cabinet. The distinct advantage of this is that it prevents thermal effects from occurring on the sensor itself as well as in the area surrounding the sensor — on the 3D tracer head, for example.

Compared to a laser sensor, this sensor has a significantly more favorable, compact design. In addition, in contrast to a laser sensor, this sensor works equally n all directions due to the coaxial light directed toward the component surface and back. The large lens aperture enables measurements with highly inclined surfaces, which are inevitable occurrences on gearings. Thanks to the system's high resolution, measurements in the sub-micrometer range are now ensured.

Reducing Measurement Times in Serial Measurement

Digitization of the entire component is an application for which optical metrology is ideally suited. For serial measurement of high-precision ground running gears, however, it is not necessary to measure the entire component geometry with a high point density. Instead, the focus is on high measuring accuracy at the level of the tactile measurement while also reducing the measurement time. For this reason, Klingelnberg has worked out a solution to this with its latest development stage in optical metrology.

In serial measurement of a cylindrical gear, the profile and lead are typically measured on three or four teeth, and pitch measurement is performed on all teeth. This tactile pitch measurement necessarily involves inserting the stylus into each tooth space. With optical measurement, by contrast, nothing is inserted into the tooth spaces. Accordingly, pitch measurement offers the greatest potential for reducing the measurement time. Through optical measurement of the pitch using one continuous, uninterrupted rotation of the component, the measurement time advantage increases with large numbers of teeth to up to 80 percent. It is not necessary to scan a large area of the

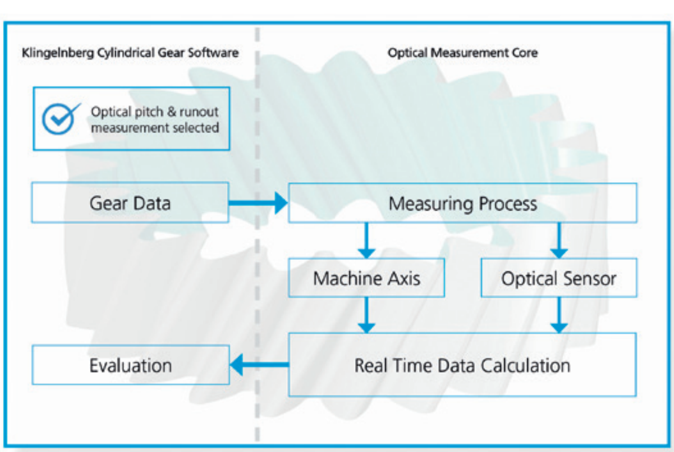


Figure 2 Schematic diagram of a measuring run.

Figure 3 Optical sensor retracted.

gear with multiple revolutions.

This optical pitch measurement is combined with the tactile measurement of the profile and lead. Overall, the total measurement time decreases by up to 40 percent. Thus in cases where there is a high utilization rate of the measuring machine, the costs for the optical metrology option are quickly recovered.

High-Precision Measuring Results

Decreased measurement time is not the only key factor, however. Just as important is a high achievable accuracy of the measuring results, even in the case of extremely complex gears with ground surfaces and steep profile angles. This is the result of intensive optimization of the sensor technology, the analysis algorithms, and the measurement strategy.

The only difference in operation is that optical pitch measurement must be selected in the same cylindrical gear measurement software customers are already familiar with. The measuring cycle is automatically modified accordingly, and the pitch measurement is performed with the optical sensor. The changeover between the tactile 3D NANOSCAN probing system and the optical HISPEED OPTOSCAN sensor takes place automatically within approximately 1.5 seconds in conjunction with the entire measuring run.

During a series of internal analyses, Klingelnberg evaluated a typical component spectrum of cylindrical gears from the area of passenger car transmissions, electromobility and gauges. In a range of gear geometries with different reflection and absorption characteristics, as well as various gearing qualities, accuracies on par with tactile measurement were achieved. The system can be used even for gears with extremely fine surfaces and roughnesses of Rz=1 µm.

To determine without a doubt whether a component is suitable for optical measurement and whether a corresponding measurement time advantage can be achieved, Klingelnberg provides customers with test measurements and demonstrations in their premises.

The More, The Better

In terms of the measurement time advantage that can be achieved, one thing is true: The more teeth there are, the greater the advantage.

Next Development Stages

The system offers great potential for further applications. In particular, for measurement tasks consisting of tactile operations involving time-consuming individual touches and complex movement patterns, optical metrology is able to reduce measurement time. But optical measurement is also ideal for fast scanning sequences on complex geometries.

Figure 4 Component spectrum

Dr. Christof Gorgels, director of product line precision measuring centers at Klingelnberg, provides an outlook: "For the further development of the system, we already have a number of ideas, including tooth root and tip measurement, axis position, roundness and other form measurement tasks. And we would like to use our customers' feedback to set priorities. That is why we are delighted at the keen interest in Klingelnberg Optical Metrology and the conversations with users that we have had as a result."

www.klingelnberg.com

A Cobot Companion

Fusion Cobotics and GAM Enterprises Collaborate on CNC Robotic Solution

According to robotics.org, collaborative robots (cobots) currently account for three percent of the total robotics market. This number is expected to reach 34 percent by 2025. Cobots are complex machines that work hand-in-hand to support—and in some cases completely relieve—human operators. They work via force sensors that allow the machines to operate on shop floors without the need for safety fences or guards. They can safely operate in the same workspace as their human counterparts.

When GAM Enterprises, Inc. (formerly GAM Gear) needed a robotic solution to load and unload parts, they collaborated with Fusion Cobotics on a potential solution. This is just one of many examples where automation, motion control and robotics are potentially altering the look and feel of the production floor in manufacturing. It hints at a future where manufacturing companies will have the opportunity to free-up their skilled workers for more important tasks while the cobots tackle the grunt work.

A Need for Added Capacity

GAM Enterprises, Inc., located in Mt. Prospect, Illinois, is a provider of precision mechanical power transmission components used in the automation of machinery. GAM has a broad product range of gear-reducers, servo-couplings, safety-couplings, clamping systems, motor mount kits and other specialized mechanical solutions.

Prior to the initial discussion with Fusion Cobotics, GAM required its own personnel to load and unload parts from its machine. Production would stop at the end of the business day and resume the following morning.

"Our production is comprised of high-mix low-volume manufacturing runs, we hire primarily highly skilled CNC setup personnel to operate our machines," said Craig Van den Avont, president at GAM. "It is not an efficient use of our CNC operators' time to load parts when they can be doing more job setups."

In addition, Avont said that the company needed more production time/capacity to run parts.

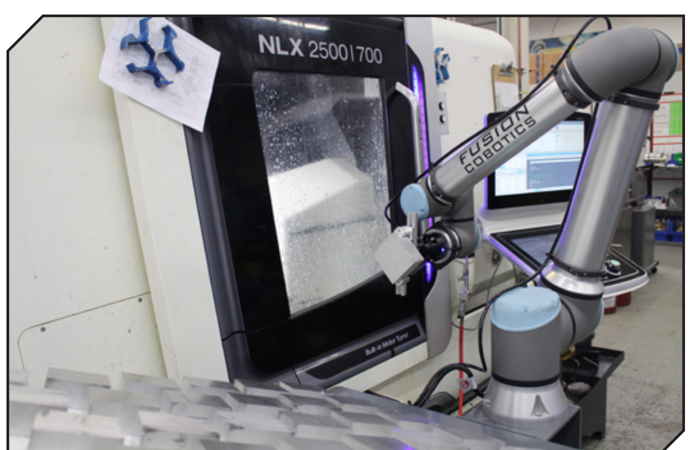
"We wanted to extend the workday into the evening in order to finish a production run and start a new job the next day," he added.

A Cobot Solution

Fusion Cobotics, located in Burr Ridge, Illinois, is a CNC systems integrator for collaborative robots, focused on automating machine tending solutions for CNC turning and milling machines to increase productivity. The company offers complete and proven, turn-key machine tending solutions that help metalworking companies become more profitable, even in small batch processing, by offering standard, affordable, easy-to-learn, easy-to-use, automation systems that can be applied to any type of CNC equipment.

Fusion installed the FC02—a CNC machine tending system based on Universal Robots' UR10e cobot—at GAM because it is an extremely flexible collaborative robotic solution that can tend to the simple repetitive tasks of loading and unloading parts from GAM's CNC equipment.

"By automating the machine tending with the Universal Robots' UR10e collaborative robot, they freed up their highly trained machinists to apply their skills to more advanced tasks such as setting-up for the next job in another machine, CNC



Fusion OEM, a Certified Systems Integrator of Universal Robots (UR), installed the FC02—a CNC machine tending system based on UR's UR10e cobot.

programming, and parts inspection," said Craig Zoberis, president, Fusion Cobotics.

The system includes a Universal Robots' UR10e for efficient, uninterrupted machine tending throughout the day and into the off-shifts (lights-out) enhancing the ROI of GAM's CNC equipment while having predictable output.

"The key feature is the nature of the Universal Robots' collaborative robot technology where humans can work safely in close proximity of the equipment without tying up valuable plant floorspace," Zoberis said.

Also, the easier to use, intuitive, conversational type programming language allows for efficient reprogramming of the equipment from job to job in a high-mix, low-volume machining department—an added bonus for the variety of work GAM handles on a daily basis.

Fusion supplied all the required hardware for the application, complete installation, integration to the CNC, required on-site training, trial production run, and remote support in case there is an issue with the equipment after installation.

GAM's production is comprised of high-mix low-volume manufacturing runs. Having the Universal Robot free up skilled operators from tedious machine loading, enables the company to use its personnel more efficiently, setting up more CNC runs.

Operational Ingenuity

According to Van den Avont, GAM treats its cobot similarly to how one uses a bar feeder on a lathe. "We set up the machine along with the cobot, then let the machine run unattended until the job is complete," he added.

"The key for us was to not get hung up trying to keep the cobot running every day and through the night. Most companies don't use their bar-feeder for every job, 24 hours a day, so why apply the same logic to a cobot for chucking jobs? We use the cobot on chuck jobs with the idea that we want to extend our workday by "X" hours to complete a job and move onto the next one. The incremental added capacity is huge," Van den Avont said.

One area that proved challenging, however, was chip control. GAM operators didn't account for the fact that every time an operator loaded a part, they also used compressed air to blow out the CNC door tracks. "We must pay extra attention to chip control to prevent nuisance automatic door jams," he said.

Future Considerations

The 'on the job' learning process has led GAM to consider expanding its family of CNC machines with cobots in the future.

"We will plan our daily operation around a setup person handling multiple machines with a cobot performing the repetitive part loading," Van den Avont said. "New CNCs will be purchased with all the interfaces and automatic door systems installed at the factory."

By examining automation, motion control and robotic solutions, machine shops can increase their output with efficient, reliable, uninterrupted machine tending throughout the day and into the evening shifts.

This enhances the ROI of CNC equipment and gives companies the flexibility to utilize their highly trained machinists to apply their skills to more advanced tasks.

"The FC02's collaborative robot allows GAM to automate safely without tying up money and valuable floorspace that is required by conventional robotic machine tending solutions," Zoberis said. "In my opinion, increased overall reach of the cobots would help with the larger CNC machines that are on their production floors."

www.fusionoem.com
www.gamweb.com
www.universal-robots.com

Gleason

IMPROVES HARD FINE FINISHING OF GEARS

DR. ANTOINE TUERICH, GLEASON CORPORATION

In conventional gear manufacturing, quality control is performed randomly. This is primarily due to the significantly longer time required for inspection as compared to the actual production time, and limitations in metrology capacity. In fine machining of hardened gears it is not unusual to inspect as few as 5% of the finished components. In order to guarantee close to 100% reliability, statistics are used to validate most of the gears produced. By deliberately narrowing down the tolerances,

GRSL Double Flank Roll Tester with Integrated Laser Checking can assure up to 100% quality inspection.

it is possible to guarantee compliance with the actual drawing tolerances with a sufficiently high probability (typically > 99.99%). This method is commonly used for machine and process capability studies, and the cmk and cpk values used as a basis are usually above 1.67. Statistically, the reject rate is only 0.57 components per 1 million manufactured components, but this means that only about 50% of the actual required drawing tolerances are available as manufacturing tolerances. Additionally, the constantly increasing power density of gears and the growing importance of noise behavior are leading to increasingly tight tolerances. Clearly, the heavy reliance on statistics poses a significant problem for a growing number of gear manufacturers seeking to achieve 100% compliance for today's very high quality gears.

Gleason's fully automated HFC with integrated grinding, washing, marking, in-process gear inspection and optional gear noise detection.

Up until now, much of the focus on production floor inspection has been on achieving objectives such as establishing a 'closed loop' connection of inspection to production machine, and putting a shop-hardened measuring machine in close proximity to the production machine to save valuable queue time. Gleason's new GRSL roll testing device with integrated laser measuring technology, however, takes a completely different approach: greatly reducing measuring time so inspection can take place within the time allotted for production. This now opens the possibility for actual, 100% inspection of all manufactured components. End result? There is no need for additional narrowing of tolerances and the 100% inspection of all manufactured components can be accomplished in-process without slowing production.

A good example of how this new inspection approach brings added value to the gear finishing operation can be found on the new Gleason Hard Finishing Cell (HFC). It's a fully automated system with robot loading that integrates modules for auxiliary processes in order to meet specific customer requirements easily and flexibly. This revolutionary concept, when presented for the first time in 2020, demonstrated a complete process sequence including Threaded Wheel Grinding, washing, laser marking, measuring and part handling in a stackable basket system. The HFC concept can also be easily applied to any desired process, with a single system replacing a number of machines.

HFC's 100% inspection capability results from the new GRSL, Gleason's latest Double Flank Roll Tester with Laser Technology, which is fully integrated into the system. The component to be tested is loaded by robot onto the GRSL. During the gear inspection, a laser scanner is used to measure all gear characteristics. All relevant information for profile, pitch, runout and—if desired—lead measurement is available. This is done for every tooth and not, as is usually the case, on just four sample teeth distributed over the circumference.

In addition, the measurement results from all teeth can be used for advanced waviness analysis using Fourier analysis to detect not only the mesh harmonics of the gear but also the so-called ghost frequencies. In many cases, depending on the amplitude, these frequencies are significant contributors to problematic noise characteristics of the gear.

Now, GRSL makes it possible to perform all these analyses on up to 100% of the gears, in real time, and without impacting precious production time. The geometrical deviations of the gear determined by the GRSL inspection are relayed back to the production machine by means of a closed correction loop. Both fully automatic correction and real-time adjustment of the corresponding parameters can be achieved. Compare that to the conventional measurement process that takes place in the Quality Lab, where 45 to 60 minutes may well pass between removing the component from the machine and providing the measurement result. With HFC's in-process inspection and Closed Loop, the desired correction ensuring optimum quality during the ongoing production process is much faster.

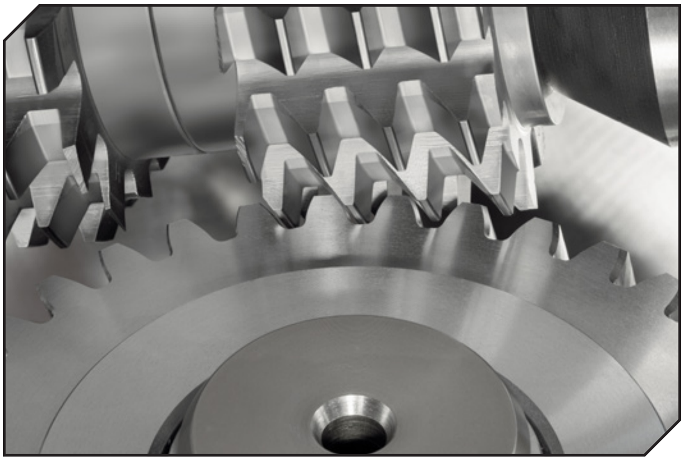
Components with characteristics that fall outside the tolerances, including noise analysis using the advanced waviness analysis, are automatically rejected. It is also possible to create extensive trend analyses of individual features and perform necessary corrections before parts get out of tolerance.

Gleason

OFFERS BURR-FREE GEARS FOR E-DRIVES AND TRUCK-SIZED GEARS

GOTTFRIED KLEIN, GLEASON CORPORATION

Cylindrical gear chamfering and deburring is perhaps the least appreciated process because it adds cost without delivering apparent improvements in gear quality. There is a growing recognition, however, that the chamfering process—if performed well—provides significant improvement in cost-per-piece as well as many benefits in subsequent handling and processing



Chamfer hobbing for burr free flanks.

New Genesis 280HCD for hobbing and chamfer hobbing or fly cutter chamfering.

operations downstream. No wonder manufacturers of automotive- and truck-sized gears are now keen on exploring new technologies to chamfer gears more cost-efficiently and with greater precision.

With development of the Chamfer Hobbing process, chamfer cutting technology has made an important leap forward. Chamfer Hobbing is a chamfer cutting process for medium- and high-volume production and dry or wet cutting of "automotive-sized" gears, designed to fulfill most of today's most common chamfer tolerances and those expected in the future. The chamfer on the left and right flank is cut in a generative mode using separate, dedicated chamfer hobs made of High Speed Steel (HSS) materials featuring an AlCroNite® Pro coating for longer tool life. The hob profile is specifically designed for the particular chamfer form to be realized. The benefits of this process are burr-free face sides of the gear as well as no measurable burr on the edge between chamfer and gear flank. As a result, gears are perfectly prepared to meet the requirements of subsequent hard finishing operations. Finally, Chamfer Hobbing brings an entirely new level of economy to this operation, with a tool cost per workpiece of as little as 1 cent.

For gears up to 400 mm and module 8 mm and smaller batch production the highly flexible Fly Cutter Chamfering process (Chamfer Contour Milling) can be applied. The universal fly cutter tool with indexable carbide inserts creates the chamfer via multiple cuts. Chamfer angle, chamfer size and chamfer form (with or without root chamfering) depend solely on programmable machine movements, providing the highest flexibility for coarse pitch gears — even with different modules, pressure angles or numbers of teeth.

Chamfer Hobbing and Fly Cutter Chamfering each provide specific benefits depending on quality requirements, lot sizes and processing strategy. Both chamfer processes can be integrated on various models of Gleason Hobbing Machines, and performed in parallel to the main hobbing process for minimum cycle time and maximum productivity.

www.gleason.com

2021 State of the Gear Industry

Reader Survey Results

Gear Technology's annual State-of-the-Gear-Industry survey polls gear manufacturers about the latest trends and opinions relating to the overall health of the gear industry. As in years past, the survey was conducted anonymously, with invitations sent by e-mail to gear industry companies – primarily in North America, but also including some respondents from around the world. More than 200 individuals responded to the survey.

All of the responses included in these results come from individuals who work at locations where gears, splines, sprockets, worms and similar components are manufactured. They work at gear manufacturing job shops as well as captive shops at OEMs.

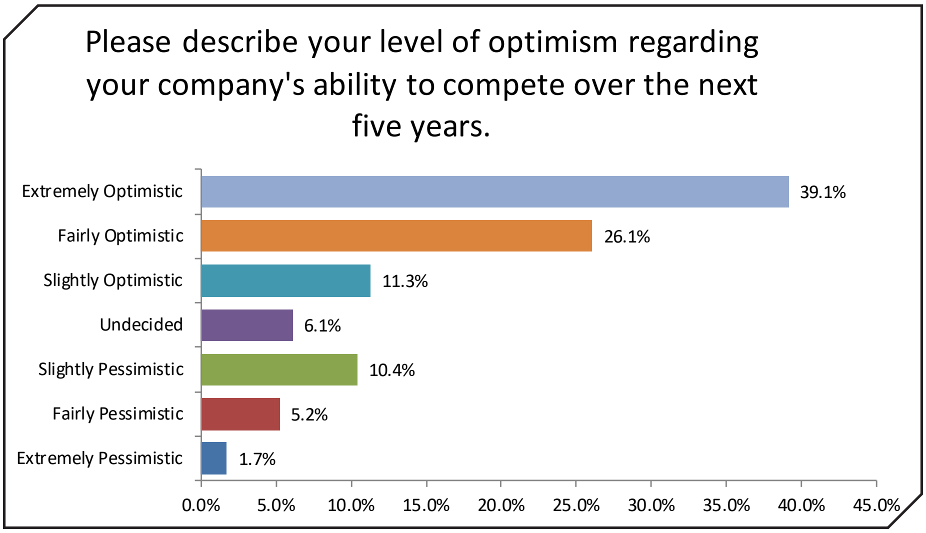
A full breakdown of the respondent demographics can be found at the end of this article.

Summary

Last year's survey was conducted before the COVID pandemic. This year's survey was conducted in mid- to late January. Both last year and this year saw historically low levels of optimism in the gear industry. In 2020, only 75% of gear manufacturing companies indicated some level of optimism about their company's ability to compete over the next five years (compared with 85.8% in 2019 and 83% in 2018 and 2017). What's surprising – after almost a full year of pandemic, economic and political turmoil – is that this year's numbers aren't significantly different overall. In fact, they're slightly improved, with 76.5% indicating some level of optimism.

The gear industry has always been a positive bunch, and they remain so even in the face of terrible conditions.

The gear industry faces significant challenges, the most obvious being the COVID pandemic. 39% of respondents cited COVID or the pandemic specifically when describing the most significant challenges facing their businesses, with many others citing the need for increased productivity, new sales development, general economic conditions and other factors that are indirectly related. As in past years, the need for finding, training and retaining skilled labor remains one of the biggest challenges our industry faces, with 21% of respondents listing some aspect of skilled workforce challenge. Here's a sampling of what's keeping the gear industry awake at night.



What are your company's most significant challenges for 2020?

Need for more capacity, without spending capital.

Government policies on environment will have tremendous impact on vehicle/equipment industry.

COVID.

Keeping suppliers abreast on the meeting requirements.

1. Restoration of the supply chain; 2. rebuilding customer trust (by breaking the supply chain); 3. Further reduction of operating costs.

US-China trade war and COVID-19 pandemic.

Becoming more efficient and improving delivery times.

Maintaining highest quality levels.

Demand shrinkage because of COVID.

Lockdown.

Increase in input material cost.

We have stayed about the same. When COVID hit we saw about a 10 percent drop in sales but now sales have returned.

Personnel.

Speed up the production.

Lockdown leading to high inventory, affecting cash flow.

Continue to satisfy the customer's needs although the pandemic forced all to have more limitations.

Just the economic challange.

Stagnant commodity prices.

We are at the mercy of OEMs building gas turbine engines. As long as air travel is restricted, volumes will not increase.

Finding skilled labor.

Head count reduction in response to pandemic closures make us more lean, despite volume demand outlook in 2021 is higher than ever. This presents significant challenge to meet the targets we have forecasted.

We want to expand export business .

Quality.

Hiring experienced engineers to replace those that are retiring this year and next.

Retaining top talent that is finding better opportunities in growing industries; connecting with new customers due to ongoing travel restrictions.

Lack of good employees.

Cost reduction, increasing efficiency.

Industry 4.0 projects.

Dealing with schedules from employees, customers and vendors. Nothing really ran smooth.

The most challenging part of 2020 was getting customers to take the parts they ordered. Or, to pay for the parts they accepted in a timely manner. The large OEMs clearly do not understand the impact they can have on small business. During 2020 we learned which customers had our backs and were willing to work with us during COVID and which did not. It was an interesting year and difficult lessons learned.

Increase productivity and throughput with the current workforce.

COVID-19 and availability of raw materials.

COVID sicknesses effecting workers.

COVID restrictions affecting customers.

Lack of proper labor force.

Keeping up with technology changes.

Maintaining sales and keeping the work force safe and working due to COVID.

COVID19.

For past year the biggest challenge was keeping the employees healthy; two colleagues left us!

COVID: working from home.

Projects have no fixed timeline or focus.

Introduction of Industry 4.0.

Electrification - Complex parts.

Improve quality and productivity in preparation for the next production expansion.

Adapt capacity.

Keeping the business running during COVID period; Management of manpower; the optimization of available funds. Maintain manpower, adjust to "new normal," maintain revenue generation to optimal level.

Ramping up.

Matching capacity vs. demand.

1. Restart after COVID lockdown; 2. Exponential growth in worldwide demand for gears; 3. Skilled manpower to match the current market demands.

Finding work and finding competent workers.

Loss of Sales.

Sino-U.S. relations & eu-china relations.

Finding qualified help, to replace someone retiring.

COVID-19.

Workforce Skilled Labor shortage.

New Business Development .

Keeping existing workforce healthy.

Installation of additional equipment and upgrading the software.

Being able to sustain the downturn till the economy picks up to 2019 levels.

Maintaining skilled workers in downturn in business.

Increase in healthcare costs and cost of living.

Shipping.

Finding niche markets that are not overwhelmed by cheap imports.

Our company is struggling to just keep our doors open since our sales were down more than 30% in 2020 over 2019.

Our plant has dealt with one COVID outbreak which caused us to shut down the plant for two weeks. Even with that, employees staggered back, so we were not at full production until about 4 weeks after the plant-wide shut down. This wreaked havoc on our schedule and deliveries to our customers.

Resources internally are spread very thin and there are many unknowns. We are hopeful sales will be up at least 10% over 2020.

There will still be a threat of COVID outbreaks, especially on the plant floor, though we have been using extreme precautions.

Improvements of soft power skiving; LPC heat treatment; Improvements of gear honing.

It is really hard to know. There is the usual, people... overall looking for the vaccine and for general life to get closer to normal.

Skilled Manpower.

We are machining parts which were previously done in a sister plant, which closed down last year. We are learning new equipment which was brought in from that plant and purchasing new tooling as a result.

COVID related issues.

Sourcing of parts as other manufactures decreased the size of their business and hours leadtimes, prices, and availability of parts all had challenges.

Maintaining a COVID safe working environment while producing parts.

Change to virtual contact.

Commercial aerospace decline, picking up new work in other various industries.

COVID-19 and finding skilled workers that are able to pass a drug test.

Massive steel price increases.

Skilled artisans in short supply.

Obsolete equipment.

Civil aerospace business being at a low level with fewer flight hours and fewer new planes.

Avoid financial loss with sales down 70% three of the last four quarters of 2020.

Maintaining manufacturing staffing. Outside process vendors reduced or limited capacity.

Having enough experienced engineers.

Maintaining employees while customers slowed orders during Q2&3. Decrease of revenue by 25% during that timeframe.

Being mainly dependent on the auto industry we can only plan in sync with them.

Reducing lead times.

Zero defects.

New product introductions, combined with high production volumes of current products, and shortage of staff due to COVID.

To stay ahead in Pandemic situation, workers issues and getting repeated orders from clients.

Cost reduction programs and automation and layout improvements.

Productivity.

The problem is a decreasing of economically active population. Growth of productivity through manufacturing automation, this is our sole solution.

Fluctuating workflow. Incoming orders have not been consistent, hard to evaluate future stability or need for additional employees or a possible need for layoffs.

Keep constant efficiency in a fluctuant capacity condition.

Finding people to train for low volume manufacturing.

Machine repair and recruiting people.

Keeping employees safe (mentally, physically and financially).

COVID shutdown based upon political situation.

Development of new projects (sales dept).

The Russia–Saudi Arabia oil price war killed oil prices in the beginning of 2020. We slowed because of that. And then COVID hit. We are a 3-man shop we have idled the shop and all of us are on unemployment.

Reduced production.

Finding qualified employees.

The pandemic.

Market conditions; Skilled people.

Finding experienced gear makers.

Visiting customers.

COVID and keeping people safe.

Keeping customers happy - price and delivery.

Hiring and keeping talented people.

Management.

The most significant challenge was adapting to the effects of the COVID pandemic without losing the vision of continued customer service.

How has the COVID Pandemic affected your business?

Minimal. One large customer has slowed significantly, but others have increased demand.

Severely.

No air travel.

Big impact.

It has impacted initially; however further trends are smoothing out.

Worse than during the outbreak of the economic crisis in 2008–2010.

Dramatically decreasing in the beginning, then uprising at the last quarter 2020.

Not at all - all systems go.

It affected during starting period but revived later in the year.

Our market shrank.

Caused reduction in sales.

Strongly.

Mainly postponed the deliveries of equipment to some customers and limited new orders.

Very strongly in all of our depar-temnts: design and construction, sales, manufaturing and assembling, shipping, service worldwide, etc. Challenging situation with all these restrictions for all employees. Home Office, how to come to the company, traveling, etc.

Substantial market activity reductions.

35% decrease in demand.

Not much.

Lockdowns on our customer plants, our plants and our suppliers have strained supply chains globally. Today, suppliers are presented with the greatest challenges as other parts of the globe recover faster.

Sales dropped.

Yes, many are working from home. Note: productivity has most likely increased. We use online meetings software, like Teams. Everyone has cell phones.

Sales is the most affected as meeting face to face with customers is very difficult, so, relationship building of trust is somewhat lost. This is also lost from working offsite.

Lost employees both due to furloughs and requests to work on site early in the pandemic.

Delay in final acceptances due to inability of service technicians to travel to sites.

Added extra precautions in day-to-day business.

A lot in spring 2020 but not much now.

Mostly, problems in replacing ill people.

Created a lot of uncertainty

COVID has crushed our Commercial Aerospace business. Thankfully we have significant Defense business with our OEM customers spread over a wide range of aircraft platforms.

Not much until the last quarter of 2020. Now a substantial downturn.

Wiped out most of Q2 production and sales resulting in layoffs/furloughs for our employees.

Increased sick leave.

Pivoted to remote work for office personnel.

2 month shut down.

Business was only slightly off target. Increase in the medical side of the business kept us close to target.

Aerospace and commercial aircraft business was greatly affected.

Fewer orders, manpower problems, material problems.

25% downturn due to some months' production stops.

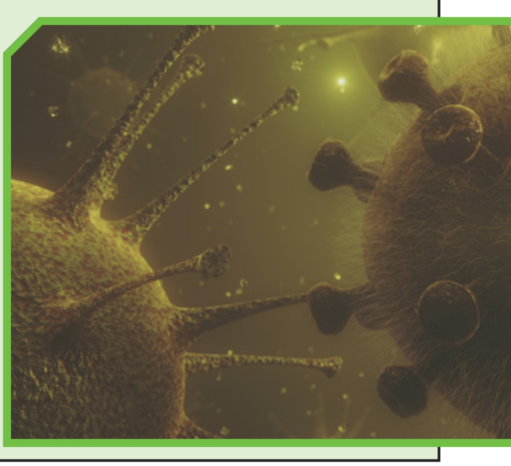
Turnover 2020 ~-20%

Reduction of new projects, regulation of business trips.

Decrease of volume in civil aviation.

Not that much.

In our company COVID pandemic actually comes with opportunities.



Our volume share is increased as many company shifted their supply base from China.

It has affected a lot in terms of business loss, less profit, severe reduction in sales and balance sheet.

Badly.

Heavy absenteeism resulting in sales loss both in-house as well as at suppliers' end.

Reduced sales and employees .

Sales reduction.

Business growth because other countries' factories closed down.

It has slowed us down.

Work stoppage.

Down 17% in 2020.

No effect.

Down 65%.

Five terrible months of new business - April to August.

Sales and profits are down significantly. Customers are not spending the same amount of money.

Financially, mostly.

Not greatly but it has decreased spending by companies, particularly larger projects that were in the works.

Slowed it down 10–14% .

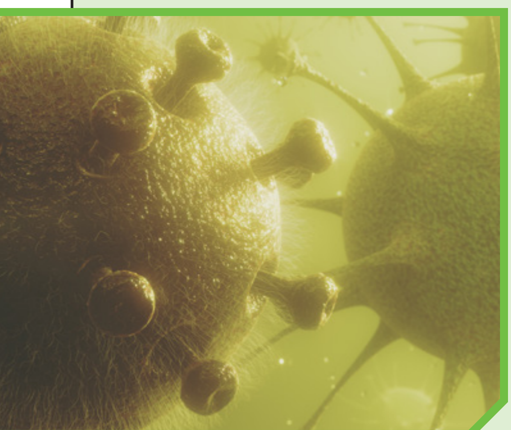
Our customers put a pause on all major maintenance spending.

Slightly.

Postponement of orders with increased costs for COVID compliance.

Very little, fewer personal visits.

Very little aside from the normal PPE use and daily temperature checks and sanitizing.



We had to overhaul how our staff worked, moving much of our office staff to work from their homes. While this was a challenge initially, our team has been resilient to create some better practices (i.e. webinars, paperless efforts). We still have 80% of office staff working from home. As our local schools have not let children attend class in person, this also poses a challenge for employees that have school-aged children should we bring everyone back in the office.

We have not shut down our facility; however, we have slowed down due to temporarily losing affected employees on a regular basis, and due to a reduction in customer demand.

We needed to put in place rapidly health regulations that were totally new before and lots of training too. Happily, our workforce responded well and the COVID impact, so far, has been manageable.

Absenteeism UP.

Slight decrease in sales but we were considered essential service and have remained open with protective measures in place as needed.

Businesses were shutdown, our office employees were working from home. Our shop employees were split into 2 shifts to try to control safe distancing and some of our production hours were spent sanitizing in between shifts to try and combat the COVID the best we could. So our sales and production were affected by that.

Severely. Because of restricted labor volumes in the mining industry the whole industry has been cut by 30–40 %.

It is back to normal now.

Civil aerospace has taken a significant hit as flight hours are only 25% of what they were. Defense aerospace has maintained with a slight increase in business.

Very bad at first beginning with the second quarter but minimal impact into the fourth quarter.

Customers put orders on hold or cancelled. Reduced sales.

Making it hard to have enough people on the factory floor.

Decrease in revenue this past year. During this time we pivoted. We put focus on rebranding, gaining new customers, new sales & increase rate of close. We did a concerted effort to connect with current customers and the partnership needs. We focused on training and retraining skills in our workforce. We used the time to improve.

Stagnated instead of growing.

About 8% reduced due to the lockdowns in many areas.

A lot. Shut down during some periods, generally lack of staff due to sick leave with mild symptoms. Suppliers have not been able to travel to us, to finish machine installations.

Around 25% business decreased, but in third quarter market has picked up and we see good growth in the coming months.

Reduction in sales and in benefits.

COVID had affected us for 45 days but now it's good.

A very unstable business environment continues.

Sales has dropped about 18%. Several employees were out for several weeks with COVID or required to quarantine which has a significant negative impact on production.

More repair, a little less manufacturing for a few months.

Increased overhead and supply cost. Also, made it harder to recruit.

Reduced hours, more time and money on PPE.

Decreased employment.

Low oil prices because of lockdowns has us shut down.

3 months of production stop.

A reduction in production and personnel.

Very little, we ran a limited crew for 1.5 months and it has been wide open ever since.

No effect on workers at this time. Some lost sales.

Eliminated sales calls.

Slowed major customers down.

Impacted by a few cases but also people that stayed home in fear of COVID. Some that stayed home to take care of relatives.

Management.

The COVID Pandemic affected sales but has overall brought a better team together to overcome this matter.

44%

of Gear Industry Companies saw a decrease in employment levels in 2020.

42%

expect employment levels to increase in 2021.

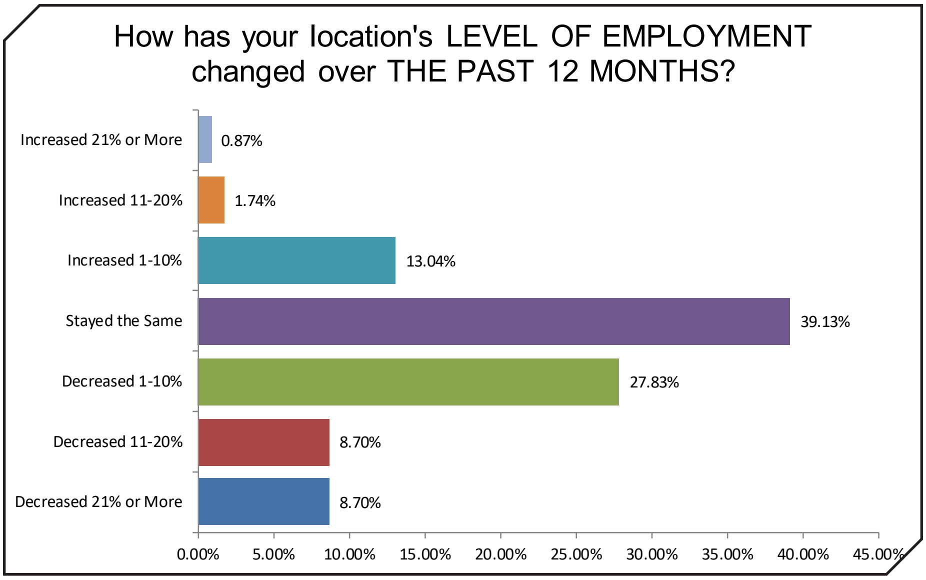
Production levels dropped at

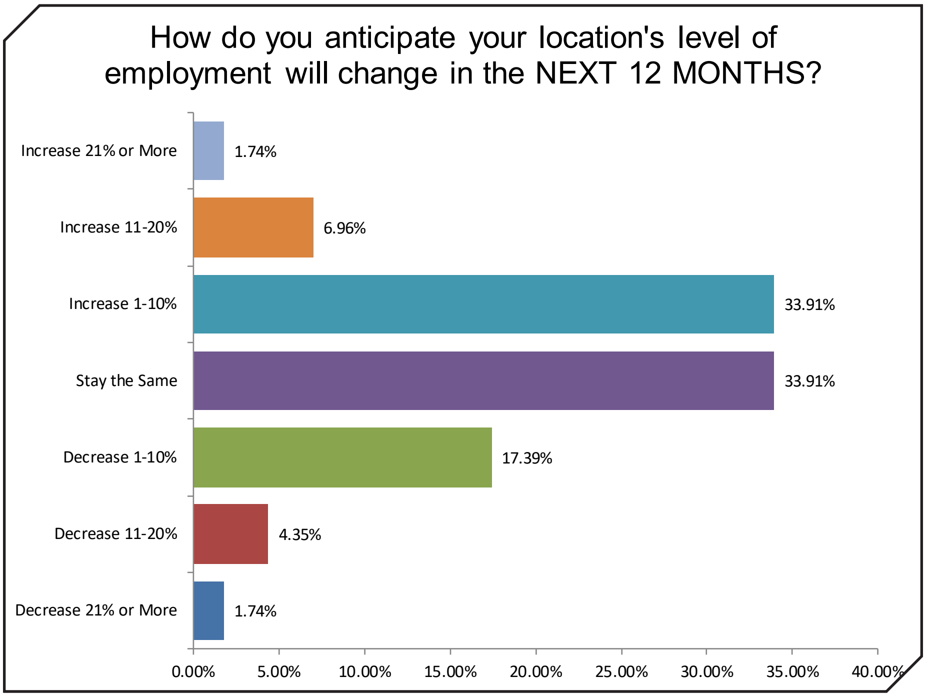
59%

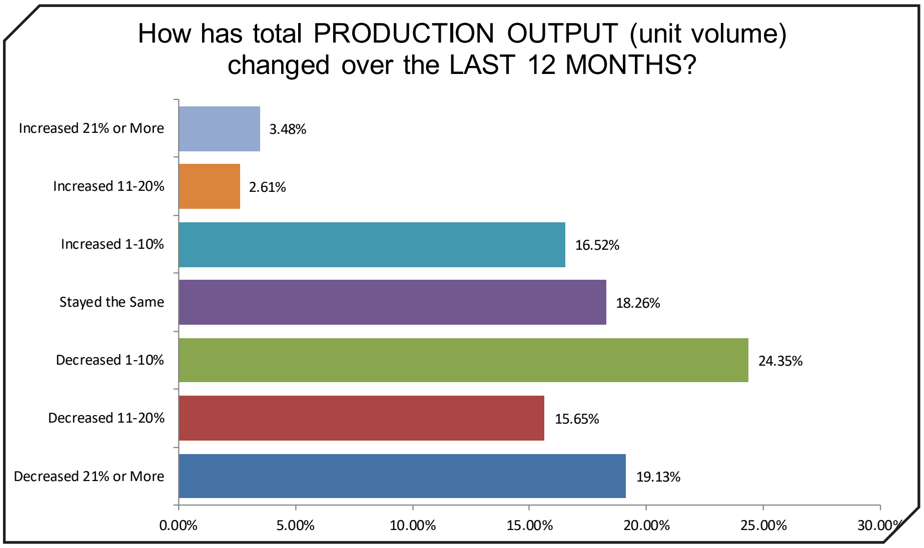
of respondents' locations.

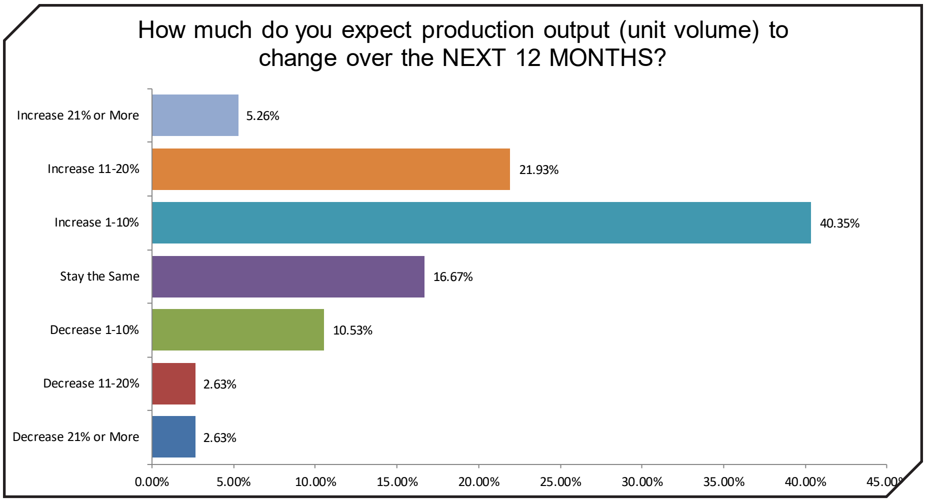
57%

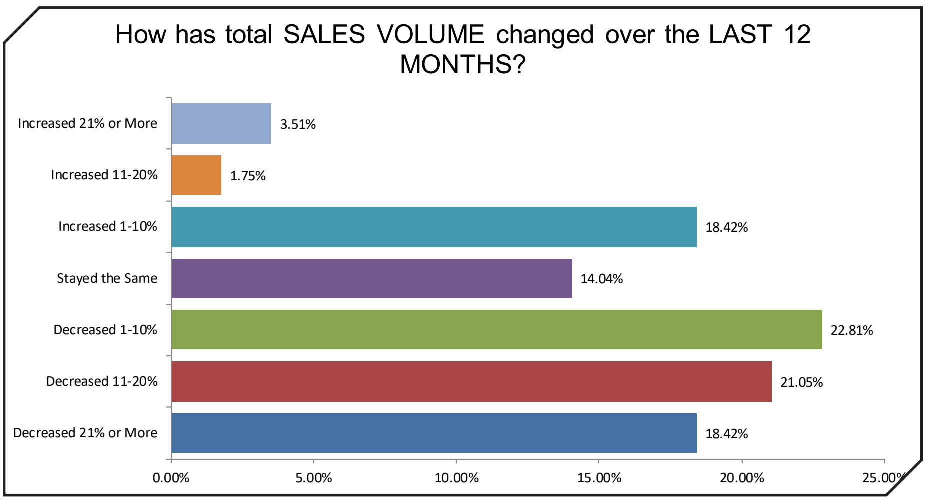
expect production levels to increase in 2021.

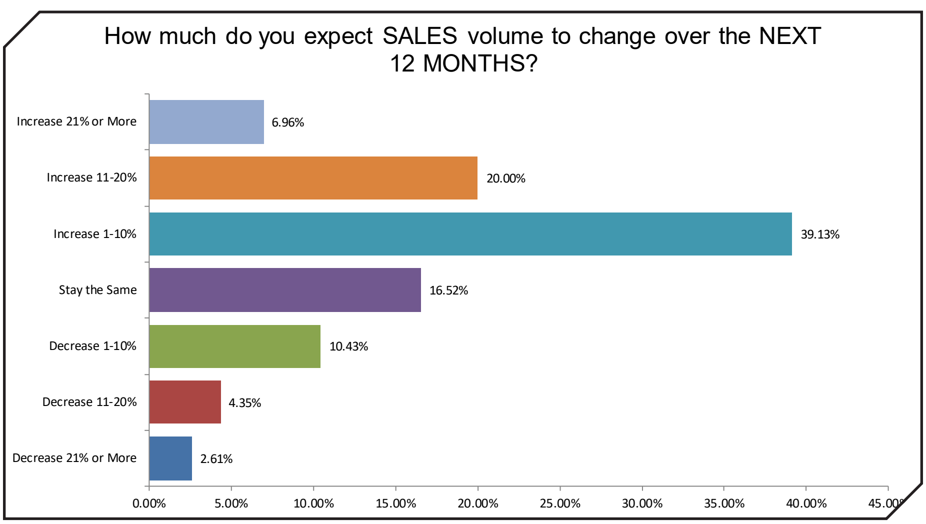












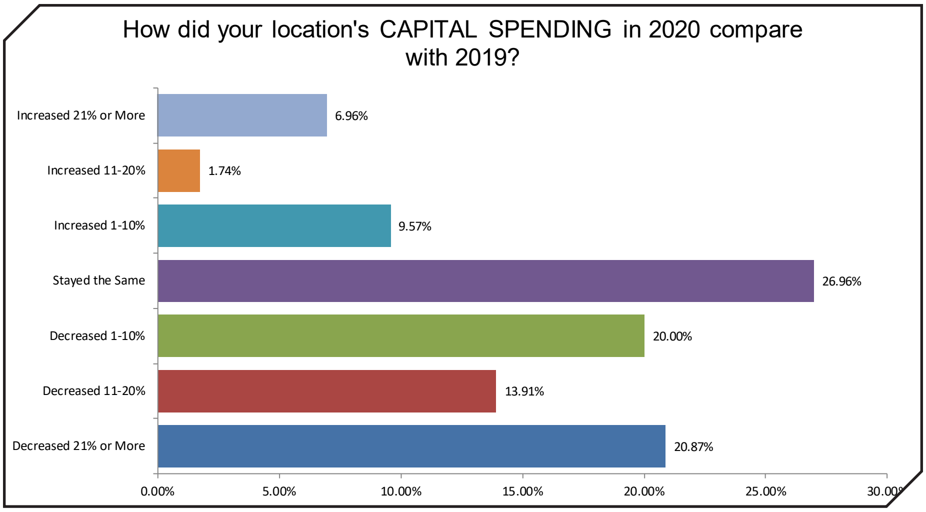
Sales decreased at

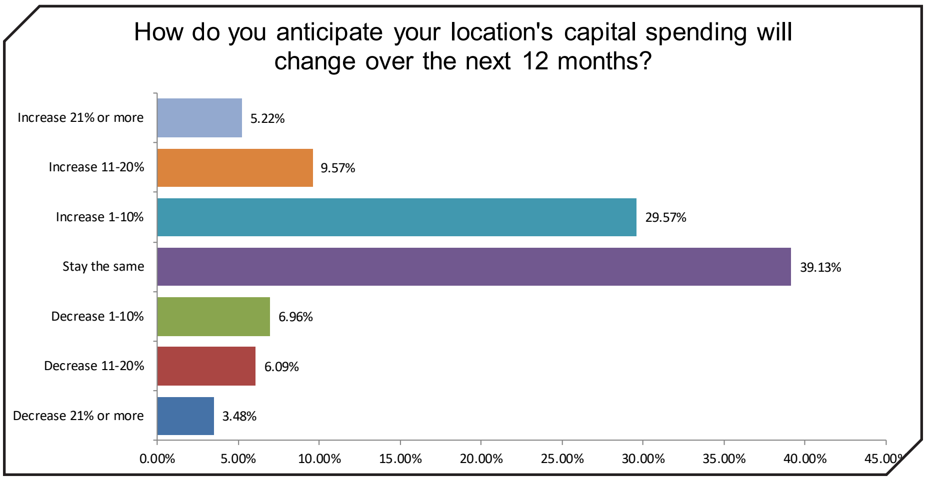
62%

of respondents' locations.

66%

expect sales to increase in 2021.





Capital spending decreased at

54%

of respondents' locations.

44%

expect to see capital spending increase in 2021.

SKILLS

What is your company doing to address the skilled labor shortage?

Automation and moving to nontraditional gear manufacturing processes utilizing standard CNC mills and lathes.

Adapt multiskilling of available manpower.

Apprenticeships.

We speak but take few actions

Initiated skill improvement.

Hiring more manpower.

We employ apprentices. Also import skilled labor.

Recruiting at apprentice level and imparting required training.

There isn't a skills shortage in precision plastic gear industry.

Training in house.

Increase training.

No skills shortage.

In-house skill development and looking for specialized training school.

Good relationships and welfare.

This is not a real problem for our company, due to the high level of our own apprentice program.

In house training of new hires.

Training internally.

Internal training.

Advanced training from within to add competencies. Aggressive hiring strategy to replace critical lost persons. Meanwhile, continued reductions in certain areas are ongoing toward leaner strategy.

We make internal training.

Train people and introduce more machines that require less people.

Just finding people who want to learn is difficult. We are working on trying to hire several. We will use one-on-one training, we have a training program that depending on one's experience can last up to 6 months then one-on-one OJT, and Seminars. This is for design engineers, application engineers and sales engineers.

Training people to improve their skills so that they can take on new roles.

Started using temp agencies to fill

in the gap, doing more training using suppliers as resource.

Recruiting extra people.

Whatever we can.

We have ongoing cross training programs throughout the facility so we don't skip a beat when someone is absent.

Cross-training from various departments.

Increasing the amount of training for current employees and working with local universities to groom potential machinists.

Working directly with colleges to gain access to candidates; Starting apprentice program.

Introducing younger students in manufacturing.

In-house training; More automation with equipment for unattended runs.

Recrutment of skilled manpower.

It's a problem. There's nothing we can do about it. Just look for trained staff, but it's not easy.

Automation.

Training in laptop skills.

Recommendation of correspondence education for employees.

Own apprenticeship department.

Training new apprentices .

We have lot of retention programs in our company.

De-skilling tasks.

Hire trainees from technical schools for short and medium term.

Training.

No solution at the moment.

Advertising and checking with the local community college.

Hope, wait.

Continue to recruit curious "hands on" workers; Promote education with full reimbursement; Promote from within.

There is none.

Training.

Nothing.

In-house training of younger employees with experienced employees.

Full training.

More advanced equipment with less manpower.

Previously, we've hired interns and worked with our local community colleague to educate potential future workers, but COVID has not allowed us to work on these projects in 2020. We will not likely pursue these efforts in 2021 due to COVID.

That is becoming a bigger and bigger problem as we purchase more complex 5-axis machines.

We have a few apprentices… we are addressing it.

Hire and train within.

We are cross training within our organization to improve the skills of our employees, as well as providing support to the local community colleges.

We are hiring more young machinists.

Currently we do not have one due to business shortage.

Encouraging mentoring and helping less experienced employees.

Cross train and develop younger talent.

Actively working in the local schools, county and state.

Training.

Offer paid training (employ people without necessary education, and pay them during it). Long term competence development plans, including support to schools and universities in the area.

Nurturing young talent and conducting training classes .

Internal and external training mainly.

Training.

We are struggling to improve the system for productivity such as ERP, PLM, Manufacturing process, etc.

Cross training or outsourcing when needed.

Expand internal training resources.

We provide on-the-job training for required skills.

More in-house training.

Internal training program.

> "Advanced training from within to add competencies. Aggressive hiring strategy to replace critical lost persons. Meanwhile, continued reductions in certain areas are ongoing toward leaner strategy."

We are endlessly training new workers and associates and transforming them into talented people.

More $ for the same jobs

Not much we can do to address the skills shortage; Luckily we have gotten some good candidates and interviewed them thoroughly and they appear to be working out so far. I think that may be due to the pandemic and some good people being out of work because of it.

In-house training is ongoing. Apprenticeships have been suspended.

Training internally, bringing people in from other countries.

Owner working more hours.

Difficult issue, need in-house training for 2 years .

Internal training along with partnership with vocational schools.

Little of which I am aware.

We educate in house.

We have all we need. None.

Nothing.

Automating wherever possible.

Hiring skilled professionals and good interns to train under them.

Working with Jr. Colleges; Working with the military.

Hire and train new workers.

Internal training.

Hiring from trade schools; paying for continuing education; internal training.

Nothing. It has been years since they have done anything.

We are continuing to recruit qualified employees as well as continuing to cross train current employees.

Significant Trends

What are the most important trends affecting the gear industry in 2021, and what should our readers know about those trends?

Hard finishing on gears, specially honing on stepped gears. 100% measuring in line with possibility to use the complete part tolerances.

Lack of qualified operators leading to need for automation

Need for flexibility as lot sizes get smaller.

ELECTRIFICATION!

In India after the pandemic the demand for mechanical aggregates has drastically dropped hence the gear demand. Traditional gear manufacturing companies can't survive during these tough times.

Innovative production process, optimum manpower minimum machines but able to able to supply during surge in demand and not to incur losses during slump period.

For us, electrification is an opportunity. Hybrid and e-drive transmissions help us justify the use of our products - which is a clear plus.

Automation.

Lack of competency at the top level of company, when technical companies are managed by the finances, it can become catastrophic.

Electrification of the car.

1. Problems with maintaining the supply chain. 2. Higher prices of materials for production. 3. Higher electricity prices.

Industry 4.0.

Smart Manufacturing.

In India, Base work at Automotive companies on electric vehicles will be kick started/ in-progress. In general the use of gears in EVs is limited compared to diesel counterparts. Still the use of EVs across the globe will be a distant dream. Hence use of gears (of current volumes) will further continue for some more years to come.

EV demand for global market in 2021.

Quality product supplied on-time; this never changes. Electric vehicle drives increasing.

New Projects and Expansions.

Magnetic gears.

Plastic Gears.

I'm hoping robotics sector will continue to grow because I make precision molded gears.

Customers are waiting for business to start up after the pandemic. In the meantime, they would prefer to keep with same units. The smart ones are taking advantage to be prepared for the future.

Training personnel and retaining them.

Electrification forces many changes in capacity and size capability for many manufacturers. I am a machine tool rep and think much change will be forthcoming.

The economy running slowly.

Biden.

Less demand for gears due to electrification.

Electric motor drive gearboxes.

Reduction in volumes. Competition from Asia.

Gears and transmission systems coming from Electrification of vehicles.

Rising steel cost, high technology cost, low penetration training technicians, minimum understanding on Heat Treatment process.

Finding the right people.

Less companies but more skills.

Car & Truck sales.

Wind power will strongly come back; in E-Drive technology the hydrogen vs. battery discussion will be pushed forward; in many gear applications the quality requirements are on such a high level, that the physical limit is nearly reached; a faster and faster gear manufacturing will be still required, so new tooling and machine techniques have to developed; Co2-neutral manufacturing will be broken down to the machine tool and where its electricity comes from.

COVID.

Additive manufacturing, 3D modeling software, simulation software, composite structures and new materials will completely transform the Gear Industry as we know it. It will also transform bearing technology.

My company supplies automotive gearing. Automotive powertrains are undergoing transformation with the introduction of electrification. Electrified powertrains have significant reduction in amount of gears to be produced. This means the market will become extremely competitive. My company is constantly developing and working on new production technologies, many of which can help to produce these new gear designs and allow cost & space saving measures. For this reason, I am fairly optimistic for our future over the coming short term outlook.

Supply side economics. At least here in the USA.

Electrification of vehicles. We believe, this means greater demand for in-line gear measurement.

1. Electrification: the change of technology as well as entering in a new technology and still a not 100% known structure of production has frozen the new project specially for the automotive industry, causing the drop down on the sales; 2. COVID-19: the pandemic has also influenced some delays of projects since begining of 2020 and is still influencing postponing many projects.

For the bevel gear set we see a big interest in the teeth finished by grinding. For the gears in general we see a high attention to the washing operation.

Automation in inspection techniques and condition monitoring of operating gears with IOT (Industry 4).

I think with the new electrical system the business of gears will be damaged because we will use more electrical parts and fewer gears.

Commercial Aircraft is down! Military Defense and Space is up!

Increasing power density and downspeeding for heavy duty vehicles is putting more stress on the lubricant and increasing lubricant temperatures. Therefore more robust and higher performing additives are needed to ensure sufficient parts lubrication to minimize wear and reduce operating temps. The slow transition from hypoid gears to e-axles in battery and hybrid vehicles will require development of new additives and compatible fluids.

I see more problems in the training of CNC operators than in any external threat called COVID-19 or recession. As long as there are people who like to do their job well, there will always be someone who needs it.

Gear units are being bought based on price. If the "catalog" says it rates and it is low cost. So what if it only lasts for a couple of years? Offshore competitors are killing the USA gear manufacturers. Did anyone say dumping?

Lack of high volume programs in US limit opportunities for multi-machine sales. Tighter tolerances and acceptance criteria of EV technology coupled with a low rate of market expansion are driving need for R&D in face of low equipment sales. Customers are considering automation to address labor shortages but are hesitant to invest due to pandemic uncertainties and reduced cash flow in 2020.

We, as customers, are looking for better efficiency, better quality, and better longevity for the gear units. This, of course, must be based on how well the end-user maintains their equipment.

Lack of employees.

In my opinion the most important trend to follow in 2021 is how the COVID-19 pandemic behaves worldwide. The world economy may take time to reactivate if the infections do not subside or if the vaccines do not reach everyone as quickly as desired.

Shortage of people who want jobs. Raw materials to produce gears. Steel market.

Move towards electrification will increase gearmotor requirements and variety.

Outsourcing of manufacturing (and with it, knowledge) to lower cost countries. Less emphasis in U.S. universities on core mechanical disciplines in favor of bio- and nano-engineering.

Noise level to be reduced.

Profile modification.

Environment - dry cutting.

Lack of trained/skilled machinists to run our equipment.

We need the new administration to continue to promote "Buy American" and "Build It In America" ! If the trend reverses we are all in trouble. Too much Automotive, Aerospace and Industrial is outsourced to foreign lower cost manufacturers under the veil of U.S. companies who in turn outsource to their own or other low-cost manufacturing facilities to compete. Made in America should mean just that. Made In America! For example, the Commercial Aerospace Industry is obviously at an all-time low. When the economy comes back alive and the airline industry returns to pre-COVID days, the U.S. gear suppliers should reap the benefits, not the foreign gear suppliers. Too many of the U.S. Aerospace OEMs have offshored products to Mexico, Eastern Europe and Asia. Keep the work in America.

Supply levels are abundant due to technology, and market demand hasn't increased through new industries.

Conversion to electric motors and transmissions.

What the impact of vehicle electrification will be along with what decisions will be made by the Biden administration regarding taxes, regulations, COVID-19.

Additive Manufacturing and milling of tooth forms on non-dedicated machines.

Cost of labor. Electrification. Pace of the increased use of E drives vs. conventional powertrains.

Electrical cars.

E-mobility with their new gearbox designs.

Noise Topics (NVH), Electric Vehicle Gearing, reshoring and the continuation of increased automation.

Reshoring will give us all more opportunities to compete.

Due to the increasingly difficult task of finding skilled labor, unattended running through shifts becomes more important than ever.

Custom tooth profiles. No burr machining. Fine pitch.

Helical gears trends are changing to Heli-bevel Gear. Also BLDC motors providing low rpm & torque. Motors with VFD providing challenges. Noise & vibrations generated in gear operations are threats due to silent operations requirement by customer. Lubrication requirement is burden to user. Hence magnetic gears with low price workout will provide better solutions in future.

E-mobility

Demand for high energy efficiency

Reliability of GEARS. Green energy. Construction equipment is getting a good response. Electrification - Less need for engine timing gears & transmission gears. Electrification needs fewer gears in weight but more complicated versions.

Shift to low-cost companies are affecting our plants in high wage countries. Strong comeback of demand. Crucial to avoid bottlenecks in supply chains. Military aviation.

UAVs.

Business jets. Trends in environmental issues. Automotive market, how fast do they pick up again? How fast will Europe and America recover after the COVID Crisis?

COVID.

Gear Industry in India is preparing to equip to meet the quality requirements of gears for electrical vehicles. However, the renowned gear manufacturers in India also are not fully aware of the specific quality requirements of those gears. As such, it is very important for them to upgrade the knowledge & to modify their facilities accordingly, as soon as possible. This is very important for them to be able to switch over to manufacture those gears without associated risks.

Electric Vehicles do not need a transmission like the AT or DCT. The electric powertrain needs only 4 gears. The current gear production requirements will be down during the next years.

The pandemic.

EV Gearbox technology is affecting the gear industries a lot and this will continue in 2021.

Tooth Honing and tooth grinding processes are in major focus. Trend of LNS (Low noise shifting) Grinding is become more popular.

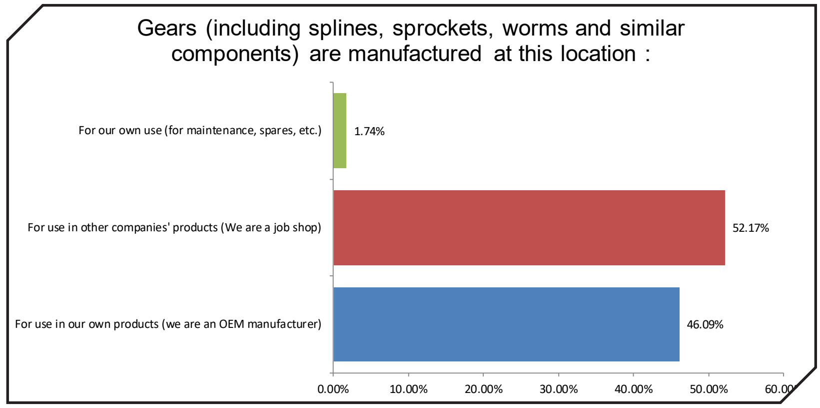
Optimizations in Profile and Lead angular errors in focus.

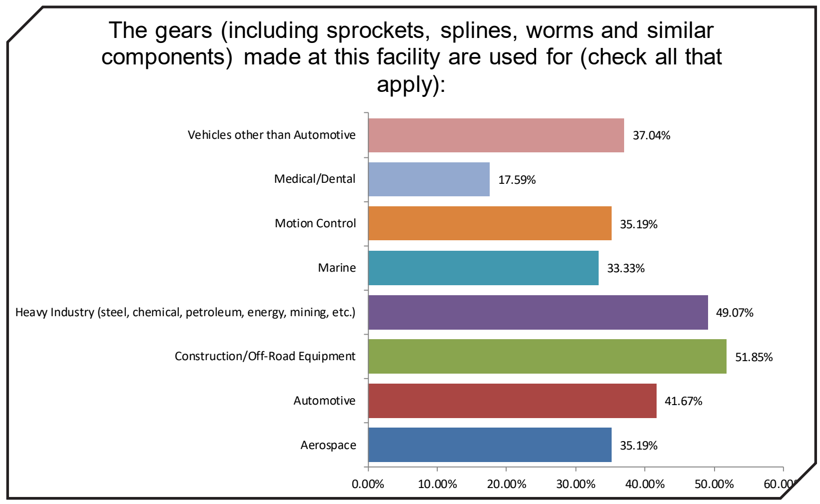
Electrification, and Energy Generation.

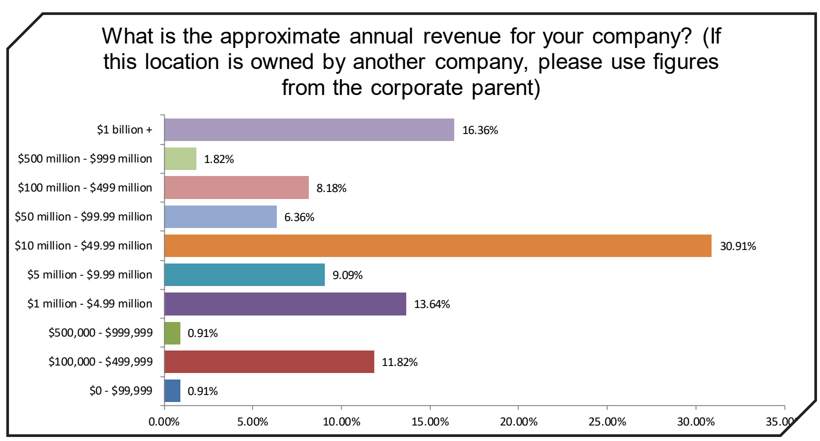
Focus on service, focus on virtual meetings, and monitoring expenses.

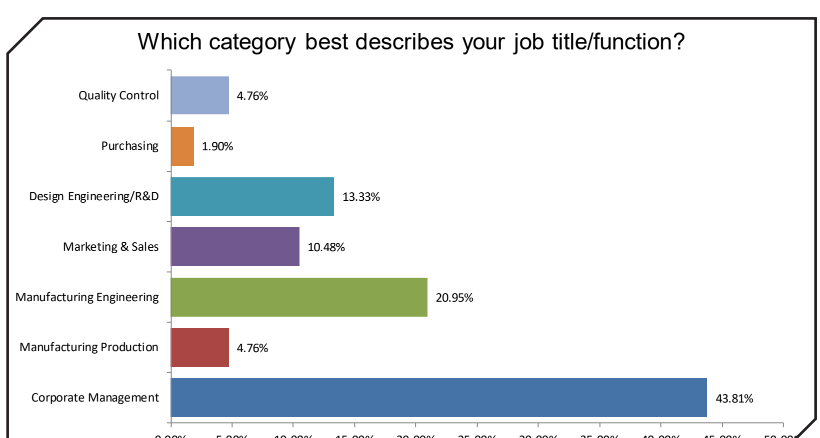
PM development, 3D printing.

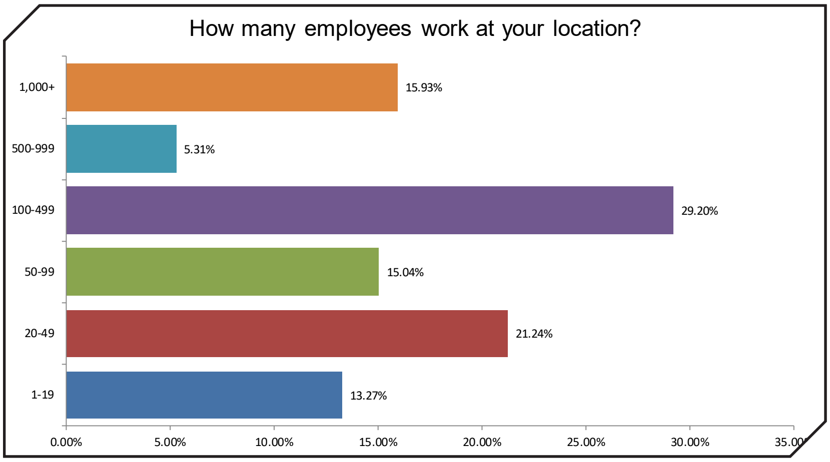
DEMOGRAPHICS

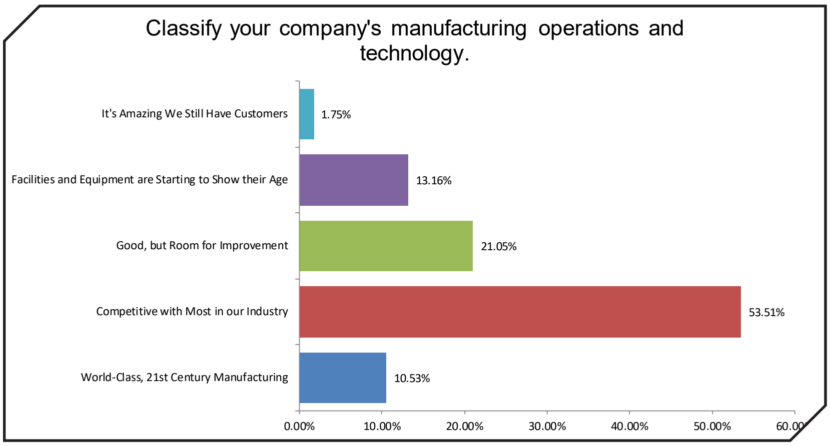


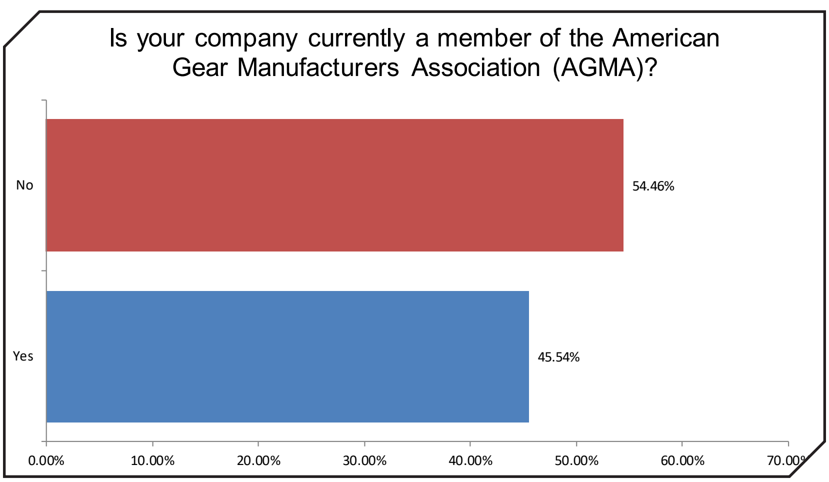












Thank you to the hundreds of participants who answered our survey. Your contribution is much appreciated!

1. Sales of Agricultural & Construct equipment on rise. 2. Transition to quieter gear box. 3. Cost competition.

Joe Biden will sell out to China and it will make it harder for all of us to find work. He will continue to pass out free money from the government and you'll never be able to hire entry level employees.

Integrated inspection, feedback control systems. Staying up to date and competitive.

Epidemic situation and Sino US relations; Large-scale; high precision; Strong Automotive demand.

The out of country sourcing is ruining companies.

Quality & reliability. The improvement in technology regarding the machinery in a gear cutting process. Economic effects from pandemic.

We shall design more lean system of rack and pinion steering system for cars, extremely the strength and fatigue performance.

No new technology advancement due to economy stagnant.

Reshoring - we see more gear manufacturing coming back to North America from Asia in 2021. E-drive - new automotive manufacturers with no gear manufacturing expertise are shopping for gears creating new opportunities for gear manufacturers.

Transition from gears alone, to power transmission solutions providers.

Retirement of family-owned businesses and both their leaders and aging employees.

5-axis machining - the future. Health care costs. Cost of living. Inflation.

Material availability, specifically high quality steel bar. Performance and racing vehicles. Continuing emergence of China as a major manufacturing force. Internal gear skiving.

Bookings for the industrial market are starting off slow. We're not seeing many inquiries. It's still very slow. Seems like OEMs aren't doing as many new projects as of yet. Likely what happens with our political climate is a key factor with so much drama going on in the U.S. We have seen some reshoring opportunities due to the U.S. being so resilient with operations during the COVID pandemic, however.

We do have concerns for 2022-2023 for the defense market, which has been a saving grace for 2020 and going into 2021 bookings. Democrats have a strong track record of cutting defense budgets. Not sure if commercial aero will be back by that time to offset potential declines in the defense market.

AGMA Standards Committees Keep the Industry "In Gear" for 2021

Amir Aboutaleb, Vice President, Technical Division, AGMA

Since publication of the first AGMA gear rating standard in 1919, shortly after the association's founding, AGMA standards development has always been driven by the needs of the industry it serves. The AGMA Board of Directors, in keeping with the increasingly global nature of the gearing marketplace, constantly reiterates the association's long-term commitment in promoting technical excellence through its leadership and active engagement on both national and international standards development.

Standards development requires dedicated individuals with proven subject matter expertise, consensus building, and many meetings. The end results are documents with benefits beyond the gear industry, such as ensuring interchangeability, creating a common language, and saving on R&D. Standards also benefit consumers by ensuring safer, cheaper and higher quality products.

The first 60 years of standards development at AGMA saw rapid industry adoption of standards and a surge in topics covered that mirrored the surge in American manufacturing. In the 1980s, the American National Standards Institute (ANSI) took notice and approved AGMA as the accredited national standards development body for gear related standards. Almost simultaneously, AGMA was approved as the administrator of the ANSI Technical Advisory Group to ISO TC 60 (International Standardization Organization- Technical committee 60)—beginning a relationship that continues to today to represent U.S. gearing interests on the international stage as a full Participant member.

In 1993 AGMA, through ANSI, was granted the role of Secretary of Technical Committee 60 (TC 60), Gears, by the International Standards Organization (ISO) in Geneva, Switzerland. The designation has provided the AGMA, and by extension, its members, a permanent seat at the table and the leading role in the development of standards used by the global gearing industry.

Today AGMA boasts a catalog of 103 standards and information sheets, developed over the years in various technical committees. AGMA has also helped create the current catalog of 59 ISO documents developed by 11 ISO working groups. Currently 362 volunteer industry experts from 203 AGMA member companies worldwide are members of at least one AGMA committee. These experts come from not only gear manufacturers, but also users of power transmission equipment, suppliers to the industry, academia, and government.

In 2020, despite the limitations imposed due to the spread of COVID-19, through 121 meetings, held virtually, members of AGMA technical committees managed to publish the following seven updated Standards and Information Sheets:

- ANSI/AGMA 9009-E20, *Flexible Couplings – Nomenclature for Flexible Couplings*
- ANSI/AGMA 6002-D20, *Design Guide for Vehicle Spur and Helical Gears*
- ANSI/AGMA 6102-D20, *Design Guide for Vehicle Spur and Helical Gears (Metric Edition)*
- ANSI/AGMA 6006-B20, *Standard for Design and Specification of Gearboxes for Wind Turbines*
- AGMA 915-2-B20, *Inspection Practices - Part 2: Cylindrical Gears - Radial Measurements*
- AGMA 945-1-B20, *Splines - Design and Applications*
- AGMA 945-2-B20, *Splines - Design and Applications (Inch Edition)*

Though at a slower pace, imposed by the different time zones its members come from, ISO TC 60 also employed virtual meetings to continue their projects and managed to publish three new documents.

- ISO 1328-2:2020, *Cylindrical gears—ISO system of flank tolerance classification—Part 2: Definitions and allowable values of double flank radial composite deviations*
- ISO 4468:2020, *Gear hobs—Accuracy requirements*
- ISO/TS 14521:2020, *Gears—Calculation of load capacity of worm gears*

Looking ahead to 2021, AGMA technical committees will continue 17 new or revised projects while ISO TC 60 will carry on with 8 ongoing projects. Here are the highlights on some of AGMA's projects:

- AGMA Aerospace committee will continue with their new revision of AGMA 911, *Guidelines for Aerospace Gearing.* Leaders in the aerospace industry, including Boeing, GE, Honeywell, Sikorsky, Rolls-Royce and others have been collaborating to rewrite and reorganize the 1994 edition to include the latest innovations in materials, manufacturing processes and other aerospace specific developments over the last 26 years.
- The widely referenced AGMA 923, *Metallurgical Specifications for Steel Gearing,* is currently under complete review and revision by industry experts within AGMA Metallurgy and Materials committee. The new version will be congruent with ISO 6336-5: 2016. It will expand the reduction ratio calculation. The metallurgical tables have been expanded to include gray cast iron, ductile iron, and austempered ductile iron. Chemistry and cleanliness requirements have also been added. An indication of the significance, and value, the industry perceives in this project can be found in the regular attendance of, and active participation by, some of the major stakeholders such as Timken, Scot Forge, Ellwood City Forge, GE, Boeing, John Deere, Caterpillar, Ferry Capitan and many others. The committee plans to publish the new version by mid-2021.
- A new revision of AGMA 925, Effect of Lubrication on Gear Surface Distress is being developed by a subgroup of the helical gear rating committee. This second edition of the information sheet will update the initial 2003 version to include information on surface roughness and gear mesh lubrication, updated calculations for gear mesh

temperature to assist with surface distress calculations for micropitting and scuffing, central film thickness calculation has been updated to include a thermal reduction factor, and the discussion of micropitting now includes a description and parameters for risk evaluation. Once completed, the new information sheet will provide the industry an alternate view and prediction methodology for one of the most important issues within the global gearing industry. The participation and collaboration on this project is amongst the largest in the AGMA standards development history, bringing together global experts from manufacturing, user, and academic stakeholders.

- AGMA Gear Accuracy committee will continue their development of a new information sheet on racks titled AGMA 943, *Tolerances for Spur and Helical Racks.* As is the case for almost all new projects within AGMA, this project is a "member initiated" project to standardize rack tolerances throughout industry and fill a gap in the AGMA publications catalog created with the withdrawal of AGMA 390.03a (the last AGMA tolerance document to include rack tolerances).
- After 5 years in development, 2021 should see the publication of the next edition of ANSI/AGMA 1012, *Gear Nomenclature, Definitions of Terms with Symbols.* Members of the gear industry should be very familiar with this standard because it is the go-to source to define all gear nomenclature. This new edition will add more definitions and align better with international standards. Standards such as this help the industry by giving everyone the common language to define various gear elements and related attributes.

In addition to the projects noted above, the following projects will see continued progress in 2021;

- ANSI/AGMA 2101, *Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth (Metric Edition)*
- ANSI/AGMA 1106, *Tooth Proportions for Plastic Gears*
- ANSI/AGMA 6008, *Specifications for Powder Metallurgy Gears*
- ANSI/AGMA 6034, *Practice for Enclosed Cylindrical Wormgear Speed Reducers and Gearmotors*
- A new revision of ANSI/AGMA 1103, *Tooth Proportions for Fine-Pitch Spur and Helical Gearing,* to update formatting, clarify the language, and include the latest practices.
- AGMA 929, *Calculation of Bevel Gear Top Land and Guidance on Cutter Edge Radius* AGMA 946, *Test Methods for Plastics Gears*
- AGMA 947, *Gear Reducers - Thermal Capacity Based on ISO/TR 14179-1*
- AGMA 955, *Information sheet on gear lubrication*
- Adoption of ISO 10064-1, *Code of inspection practice — Part 1: Measurement of cylindrical gear tooth flanks*

ISO currently has 8 documents under development. Important highlights include:

- A new edition of ISO/WD 21771-1, *Gears — Cylindrical involute gears and gear pairs — Concepts and geometry.* This new document will update equations and nomenclature to the latest practices, and will be heavily based on AGMA's standard on the subject, ANSI/AGMA 2002
- After receiving over eleven hundred comments on the draft version of IEC/AWI 61400-4, Wind turbines — Part 4: Design requirements for wind turbine gearboxes, 2021 should see the new edition published. Wind turbine gearbox design has been a hot area to standardize ever since the rise in green energy and realization of how expensive and difficult the gearboxes are to service. The number of comments received showcase the interest in this standard internationally.
- Working Group 6, which deals with gear calculations, plans to continue work on their current projects which include a new document on TFF Example calculations, Pitch vs. Reference Circle, Method B for determining K_Hbeta, and Form Grinding, Y_F

A full listing of AGMA technical committees, including a scope of their activities, can be found in the *Technical Committees* section of the AGMA website, *www.agma.org.* For additional information about AGMA technical committees, standards, and information sheets, please contact the AGMA Technical Division at *tech@agma.org.*

On behalf of the U.S. as well as the Global Gear Industry Gear Users everywhere, AGMA wishes to thank everyone who through their dedicated participation and indispensable contributions have helped and will continue to help develop these standards that have benefited our industry for more than 100 years. Looking forward to the next 100.

Thank you.
Cheers.
Your team at AGMA Technical Division

AGMA Welcomes Non-Members to Join AGMA and Drive The Future

AGMA encourages all gear companies to join and actively participate in the standards development process. Aside from having a seat at the table when AGMA standards are developed, all members receive, annually, a complementary set of all active (published) standards; a value of $3,750 for non-members who pay for the standards via www.agma.org.

Moreover, joining AGMA means you are standing up for the industry and help ensure another 100 years of technical excellence and advancement for the gear industry. Consensus-driven standards are the most important tool that AGMA delivers to the industry, and we look forward to continuing that tradition with our current members, and future members helping to add value.

Visit the AGMA website here: https://connect.agma.org/dtable to see the complete list of open AGMA documents, and the ISO website here: *www.iso.org/committee/49212/x/catalogue/p/1/u/0/w/0/d/0* to see the complete list of open ISO documents.

Amir Aboutaleb
VP Technical Division, AGMA

That Industry 4.0 Digital Factory Thing — Part 3

Joe Arvin

Welcome to the third installment of an article which is presented as a guide for navigating the topic of the Industry 4.0 Digital Factory. In the first part, featured in the August 2020 Issue of *Gear Technology Magazine*, I presented a fictional account of a Zoom meeting between me, a gear company president named Phil (a fictional character) and Chuck Gates — a very real person and one of our AGS consultants who is very knowledgeable on Industry 4.0.

In the first installment, Phil learned not to panic, for there is a methodical approach for evaluating what should or shouldn't be done. He also learned about the multi-phased approach for assessing and implementing the Industry 4.0 Digital Factory, and the specifics involved in Phase 1.

In the second part, featured in the September/October 2020 Issue of *Gear Technology Magazine,* I presented a discussion about Phase 2 — Plan of Action for the Industry 4.0 Digital Factory.

In this final episode, we continue the conversation as Chuck outlines the steps involved in Phases 3 and 4.

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Chuck: So Phil, how did you do with the steps of Phase 2?

Phil: We've developed our action plan and I think we're on track for the next phase.

Chuck: Excellent. With your action plan in place, you're ready for Phase 3, which is when you begin implementing that plan and begin to see improved business results.

Phil: Can you provide some ideas on how we can be successful with our implementation activities.

Chuck: Sure Phil. A transformation to a digital factory has many common traits with other improvement projects you've taken on in the past. But there are some significant differences. So, let me share some thoughts on how to be successful.

First of all, implementing Phase 3 of the project will require a few key elements. Because of the time and expense involved, support from **Upper Management** is essential. Also, a solid project management organizational structure and monthly monitoring will be critical for assuring optimal business results.

Phil: I would say that we have the support, the structure and systems for this type of project.

Chuck: That's great. As we talked about before, the key to being successful is to select advanced technologies that provide the best return on investment. After all, that is your ultimate goal when making these kinds of investments. And while no one is usually overly excited about spending a lot of money, I would generally say that doing something is wiser than waiting and doing nothing. Catching up later can be very painful and risky. As I've mentioned before, having a proactive plan is much better than taking a reactive approach.

Previous Arvin's Angle Articles

In case you missed any of them, here's a list of previous articles by Joe Arvin, with issue and page number:

*Visit **www.geartechnology.com/issues** to browse the archive.*
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Aside from investing the money for this project, there is another inherent challenge that you will probably face. Moving from a company's current operational processes to advanced technologies is never easy. But then couple that challenge with other issues like the COVID-19 Pandemic, the global economy, the social and political environment, federal and state regulations, among others, it can get fairly daunting. These variables can make it almost overwhelming to consider making continuous investments for the purpose of sustained competitive advantage. This will require a great deal of focus.

Phil: Oh, I completely agree. Another challenge we have is keeping up with all the technology.

Chuck: Staying up-to-date on the trends for the digital transformation and potential opportunities for the Smart Factory 4.0 is certainly a challenge that everyone is facing. I would suggest that your team take advantage of the many technical articles available from resources like *Gear Technology* Magazine, as well as the American Gear Manufacturers Association (AGMA), and the Society of Manufacturing Engineers (SME).

Leaders in the gear industry need to be aware of the technology enablers that are available in order for them to handle product variety and volume more effectively and efficiently. This information is essential for deciding on a digital transformation strategy.

Phil: I understand. When we're ready to move on to Phase 4, what insights can you share?

Chuck: After implementing the advanced technology projects in Phase 3, you will demonstrate the willingness and ability to move to Phase 4, which I call "Step It Up." The goal of this final phase is to further expand the number of Industry 4.0 Smart Factory technologies in your operation.

Think of Phase 4 this way, Phil. Before you Step It Up in Phase 4, you must take a look back and evaluate just how well you have done with the previous phases. Only then should you proceed to Phase 4.

If the previous phases are not progressing as quickly as you'd like, don't be frustrated. I generally tell people that the first three phases can take anywhere from nine to twelve months to accomplish. The point to remember is that you are moving in the right direction for future success. I like to tell people that it is not how fast you start; it is how well you engage and stay focused on continuous improvement.

Keep this in mind as well: Achieving a sustained competitive advantage by deploying a digital transformation is a journey with no finish line. It's never over. Continuous process improvement is in fact continuous.

So, before you proceed to Phase 4, here's what you really need to look at from the previous three phases. If the business results achieved in the initial first three phases were less than expected, then you might want to repeat the first three phases again. This is a conservative approach.

On the other hand, if the business results achieved from the initial first three phases were acceptable, then kicking it up a notch with Phase 4 is in order.

This is important to understand. In Phase 4, you will be going back and utilizing the same basic steps you took in Phases 1–3.

Again, here are those steps. First, you need to research and identify additional potential technologies to integrate. Next, you will develop your action plan. Then you will implement that plan. And finally, when that's complete, you will Step It Up again. As I said, continuous improvement is just that — continuous.

When you get to the point of stepping it up again, it will be time to map out the future projects for the next two years. This cyclical pattern provides you with a continuous digital transformation system.

To be honest; managing all of this takes a great deal of work. If needed, you might consider bringing in an outside resource who is experienced in providing guidance to organizations going through this process. And be sure to realize, there will likely be Industry 5.0 in the future. Progress and the advancement of technology will never end.

Phil: This has really been enlightening. But when you break it down like this, a lot of your methodology sounds familiar to me. In fact, it has a lot in common with the way we've always evaluated technology improvements. We have a long history of re-investing in the latest technology. Isn't the process of investing in the Digital Factory a continuation of the same approach?

Joe: You are 100% correct, Phil. The new manufacturing technologies of the Digital Factory are exactly that — new technologies. Perhaps the only new variable is that the technology is advancing so quickly. But it's important to resist the temptation to run out and buy everything that is available because someone has told you that without all of the new technology, you're going to go out of business. I've been saying this since the late 1970s, and I'm sure you'll agree. You must continually reinvest, just like you've done in the past. But you must base your investment decisions on the direct benefit to servicing your customers and being competitive. What Chuck has described in our discussions is the best practice for making these decisions in the era of the Digital Factory.

Chuck: Joe's right on target, Phil. It's important, just as it always has been, to be as up-to-date as possible with the latest technology. And for those who wait, more than likely, they'll have to struggle to catch up later.

Phil: Thanks, Chuck and Joe. These insights are really going to help as we move toward our transformation to the Digital Factory.

Final Words

This "Industry 4.0 Digital Factory Thing" is really not some elusive black magic or industrial alchemy. So, don't get too overly concerned. It is all understandable and manageable once you break it down and figure out what is most usable for your factory. As technology continues to progress, there will undoubtedly be more buzz words to dazzle you in the future. With this in mind, remember maintaining the status quo is really moving backwards. There are lessons to be learned from what happened to the U.S. machine tool and auto industries for what they didn't do in the 1960s and 1970s.

It is my hope that this series of articles has provided you with some valuable insights as you navigate the landscape of the Digital Factory era. I would like to thank Chuck Gates for his knowledge on this subject and his contributions.

And finally, in view of the rough year we had in 2020, I would like to wish everyone a successful 2021.

Chuck Gates received his Bachelor of Science degree in Management from the University of Illinois and his Master of Science degree in Industrial Technology from Purdue University. Chuck worked at Caterpillar for forty years in numer-ous roles encompassing Gear Machining, Gearbox Assembly, Quality, Engineering, Training, and Management. He has received numerous Professional Certifications and Awards including that of Certified Manufacturing Engineer CMfgE. In addition to teaching a wide variety of Professional Certification Review Courses, he has taught at the col-lege level as an adjunct professor since the 1990s. Chuck is on the roster of consultant resources for Arvin Global Solutions.

Joe Arvin is a veteran of the gear manufacturing industry. After 40 years at Arrow Gear Company, Joe Arvin is now President of Arvin Global Solutions (AGS). AGS offers a full range of consulting services to the manufacturing industry. His website is *www.ArvinGlobalSolutions.com* and he can be reached by email at *ArvinGlobal@Gmail.com.*

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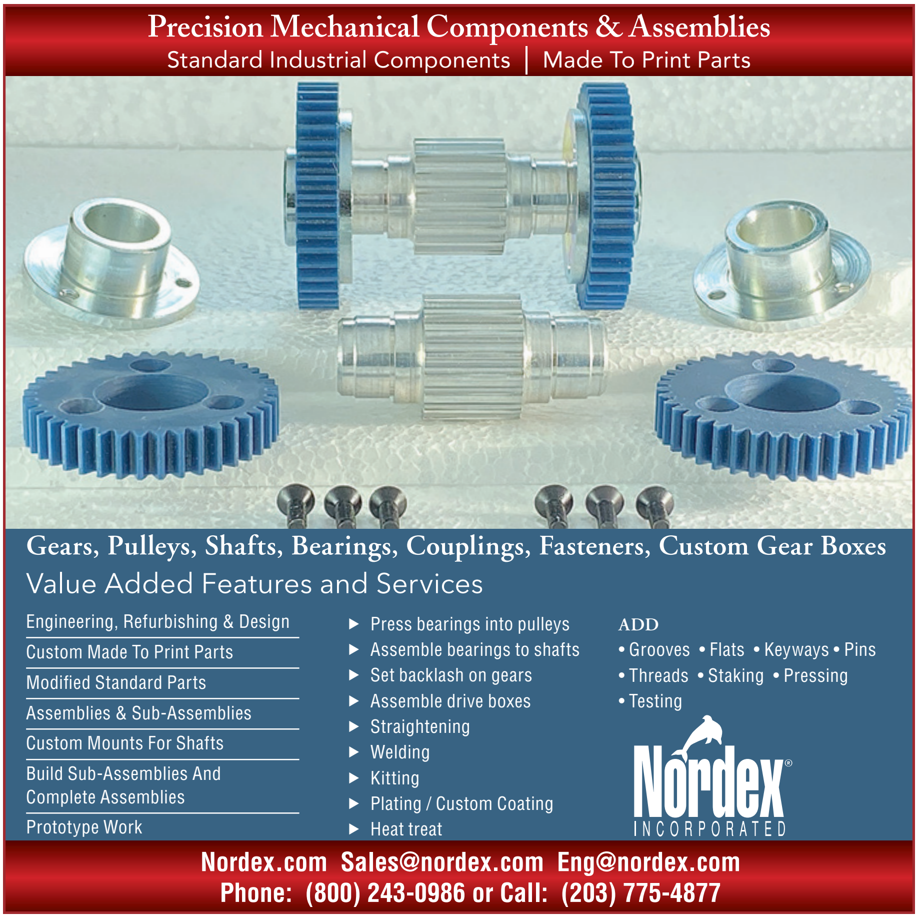
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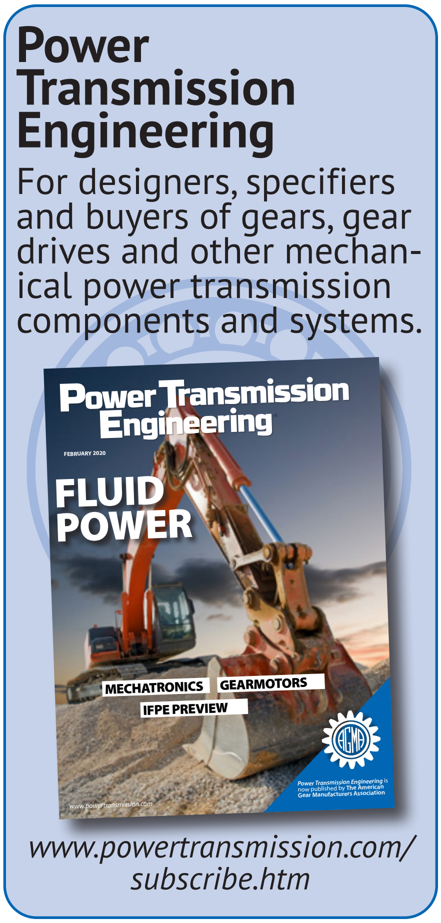
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The Hunting Tooth and its Effect on Break-In

QUESTION

Has there ever been any experimental verification of the benefits of designing a gear pair to have a "hunting tooth" or is it just theoretical?

Expert response provided by Dr. Hermann J. Stadtfeld

Introduction

When referencing the literature, it will be noticed that there is no comprehensive explanation with visualizing graphics about the hunting tooth and its relationship to the performance of a gearset. This is the reason why this article turned out larger than expected for the answer to the question, "Is the hunting tooth a more academic phenomenon, or is there a practical application?" The expression "hunting tooth" is a descriptive term created in the practical world. It describes that each tooth of one member chases and then touches each tooth (or slot) of the mating member after a certain number of revolutions.

In the case of an integer ratio for example 10×30, there will be three pinion revolutions and one ring gear revolution until the cycle repeats (Ref. 1). This scenario is graphically shown in the matrix in Figure 1. One gear revolution is shown in the top row in blue, labeled "A." The pinion revolutions are shown in row "B" and "C." The first pinion revolution is shown in green, the second revolution in maroon and the third in yellow. After this sequence, the colors repeat. For example, pinion tooth 1 will mesh strictly with the slots 1, 11 and 21 of the gear. The second sequence of pinion revolutions in row "C" is merely a repetition of the first three pinion revolutions in row "B." The pinion rotation blocks do not shift because of the integer ratio.

In the case of a ratio 12×30, which has a common denominator of 2 but is not an integer ratio, pinion tooth 1 rolls with the gear slots 1, 13, 25, 7 and 19. It takes two pinion revolutions until the cycle repeats (see Figure 2). It could be speculated if the scenario shown in Figure 2 has advantages to the scenario in Figure 1. Nevertheless, in both cases, the pinion teeth mesh in groups of gear slots. In Figure 1 these are three groups and in Figure 2 these are five groups. Only meshing between the groups is possible for the defined ratios.

A hunting tooth relationship in gear pairs means that there is no common denominator between the number of pinion and gear teeth. As a result, every tooth of the pinion will mesh with every slot of the gear. After all teeth and slots have been rolling with each other, the cycle repeats. The cycle repetition happens after the gear performs a number of revolutions, equal to the number of pinion teeth. This is of course also true if the pinion preforms a number of revolutions equal to the number of gear teeth. The number of revolutions to achieve "one tooth hunting sequence" is independent from the fact if the number of teeth are prime numbers or if simply one number is even and the other number is odd.

In Figure 3 it is graphically demonstrated how revolution by revolution of the pinion the green, maroon and yellow blocks shift from row to row. It requires the pinion revolutions in rows "B" to "L" until one hunting tooth sequence is finished. Row "M" has the identical phase relationship as row "B" and therefore presents the first repetition

The shifting of the pinion revolution blocks from row to row in Figure 3 allows, in each pinion revolution, each pinion tooth to mesh with a different gear slot. However, in one revolution each pinion tooth can only mesh with one gear slot. In order to cover all gear slots, the pinion has to rotate for each gear slot once which is then called the hunting tooth number of rotations.

Ratio 10 x 30

A = Gear Revolution

A	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
B	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
C	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10

B = Pinion Revolutions

C = Repetition of Pinion Revolutions

Figure 1 Integer ratio 10×30.

Ratio 12 x 30

A = Gear Revolution

A	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
B	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6
C	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
D	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6

B = Pinion Revolutions

C = Repetition of Pinion Revolutions

Figure 2 Common denominator ratio 12×30.

Is the Influence of the Hunting Tooth Theoretical or Reality?

It is stated in older literature that a hunting tooth ratio is helpful in the case of lapped gears. However, in the case of not heat treated or ground gearsets, the older literature points out that integer ratios are preferred. As a reason it is mentioned that gearsets with integer ratios are easier to inspect, test and assemble accurately (Ref. 2). This rule is still applied today for precision actuation with moderate to low load. The following sections will reveal that for power transmissions the effect of break-in is an extremely important factor which has a key influence to the operating performance of the transmission during its lifetime. However, if the break-in improves or worsens the performance of a power transmission depends on the optimal interaction between all teeth, which is only given with a hunting tooth ratio.

A typical single flank variation of a ground gearset is shown in Figure 4. The graphic shows a harmonic deviation over one gear revolution and three harmonic waves from the three pinion revolutions. The high frequency content is created by the tooth mesh which repeats in the graphic 30 times.

The influence of the hunting tooth is not an academic effect, which in theory would improve the performance of a gear pair. To the contrary, there is a very simple and very easy detectable, practical difference between a gearset with a hunting tooth and a gearset with a common tooth count denominator; this difference becomes tangible during the gearset's break-in.

Independent from the fact if a gearset is ground, honed, lapped or not hard-finished at all, there are certain flank form deviations from tooth to tooth and there is an indexing error; the break-in will go a quite different path in case of integer ratios. In the case of a 10×30 ratio, the three sections of the larger gear will mesh with the 10 slots of the pinion. Tooth 1, 11 and 21 will therefore only contact slot one of the pinion. During the break-in period, teeth 1, 11 and 21 will become similar or even equal to each other. The pinion teeth 1 to 10 will become more and more different to one another. Figure 5 shows a single flank variation of the 10×30 gearset, after it is broken in. The graphic shows lesser harmonic content, but larger runout amplitudes during one gear revolution. The break-in did not improve the gearset's single flank quality. The three sections of the pinion revolutions manifested a distinct single flank pattern, which is less favorable than the initial single flank variation after grinding. Superimposed to the pinion runout are the single tooth ripples from the tooth meshes. The graphic in Figure 5 represents the discussed integer ratio of 10×30 after break in. It appears that certain errors are created as the break-in progresses.

There is no influence from one section to the other two sections. Due to the integer ratio, the three sections develop independent from each other and stay after break-in basically in a permanent condition.

Because the break-in degraded the quality of the gearset performance, it is recommended to super-finish ground gearsets with integer ratios. The super-finishing will prevent a further break-in, which in this case is an advantage because it will preserve the initial motion transmission quality after grinding (Fig. 4).

Ratio 11 x 30

A = Gear Revolution

A	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
B	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8
C	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5
D	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2
E	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10
F	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7G
G	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4
H	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1
I	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9
J	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6
K	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3
L	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11
M	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8

B = Pinion Revolutions

M = Repetition of Pinion Revolutions

Figure 3 **Hunting tooth ratio 11×30.**

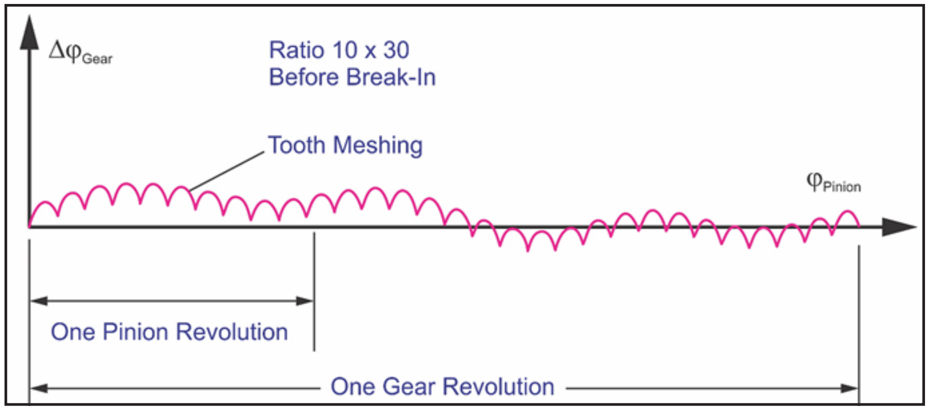

Figure 4 **Single flank graphic after grinding.**

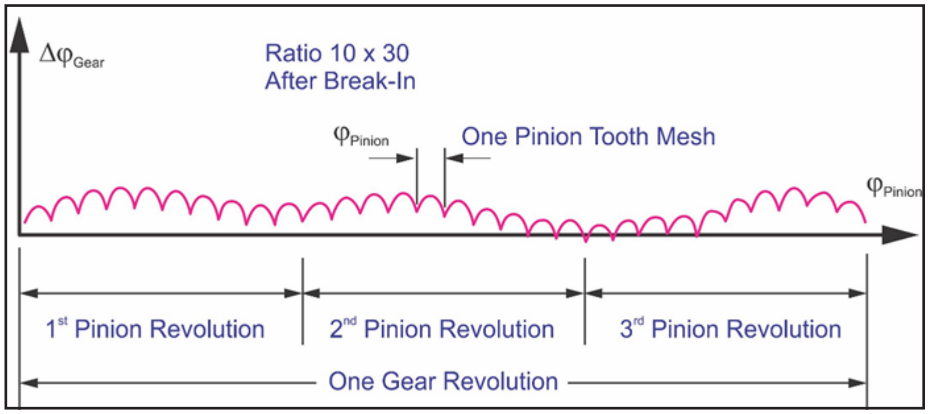

Figure 5 **Single flank graphic of gearset with integer ratio after break-in.**

Servicing a Transmission with Integer Ratio

If one of the two gears is removed during servicing the transmission, then it is important to mark a tooth of the gear and the pinion slot it rolls with. If that is not done, and the gears are assembled in a random orientation, then a much bigger problem occurs. At the time of servicing, the tooth surfaces had already been broken in and a second attempted break-in with different tooth and slot combinations will fail because the surfaces are too smooth and the hydrodynamic oil film separates the flank surfaces. However, the larger motion error in higher load conditions can cause the flank surfaces to break through the oil film and damage the flank surfaces. In many known cases, the noise level of a randomly assembled, already broken-in gearset with integer ratio increased. This would often lead to the false concern that pre-loads had been wrongly adjusted or that the bearings were contaminated during the service call.

The Break-In Procedure

Break-In is an abrasive action which changes the micro-geometry on the flank surfaces. A controlled break-in begins with light load and moderate RPM. Reversing the hand of rotation is recommended after only 20 minutes of operation.

Figure 6 shows the recommended break-in cycle for Super Reduction Hypoids. The surface in areas which cause a momentary acceleration impulse will be abrasively altered more than areas without acceleration. Areas which cause a momentary deceleration will show little or no surface alteration.

The surface action is a combination of removing sharp peaks and then super-finish them with a mix of abrasive removal and a plastic deformation. This explains that broken-in gearsets have a polished appearance on the active areas of the flank surfaces.

First the load is increased in the cycles 1 through 4 while the speed is 50% of the nominal speed or below. During this low-speed load increase, the superfinishing action is also increased. The flank form modifications during the low-speed and light-load break-in period improve the noise vibration and harshness (NVH) properties of the gearset (cycles 1 & 2) — especially in low-load operating condition — when transmission noise is most critical. The following two cycles 3 and 4 with low speed and high load cause larger tooth and flank surface deflections without having a sustainable surface separation due to hydrodynamics. This condition activates the removal of roughness peaks in the remaining areas of potential tooth contact and also polishes these areas. This section of the break-in prepares the gearset for high-load operation regarding effective contact ratio and optimal surface finish for optimal elasto-hydrodynamics.

Cycles 5 through 8 operate with the maximal RPM for which the gearset is rated. Cycles 5 and 6, where the load is lower, are dominated by a polishing effect accompanied by very small abrasive action; there is no abrasive action expected in cycles 7 and 8. The high speed and high load will initiate a final surface polishing. The duration of the entire break-in is 16 hours, which is realistic for a higher reduction gearset with a module at or below 3mm.

SRH Break-In	Direction	% of max. RPM	% of max. Load	Duration minutes	Repetitions
Cycle 1	Drive	50	25	20	3
	Coast	50	25	20	
Cycle 2	Drive	50	50	20	3
	Coast	50	50	20	
Cycle 3	Drive	50	75	20	3
	Coast	50	75	20	
Cycle 4	Drive	50	100	20	3
	Coast	50	100	20	
Cycle 5	Drive	100	25	20	3
	Coast	100	25	20	
Cycle 6	Drive	100	50	20	3
	Coast	100	50	20	
Cycle 7	Drive	100	75	20	3
	Coast	100	75	20	
Cycle 8	Drive	100	100	20	3
	Coast	100	100	20	

Figure 6 **Break-in cycle for super reduction hypoids (SRH).**

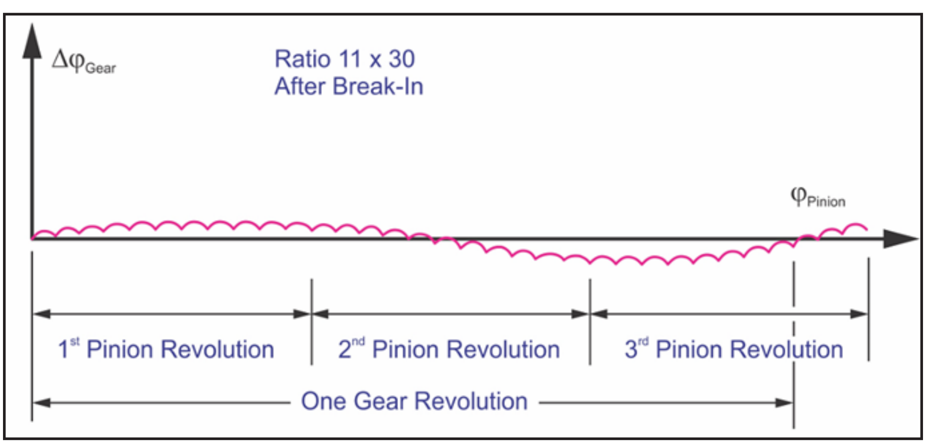

Figure 7 **Single flank graphic of hunting tooth ratio 11×30 after break-in.**

Surface Optimization during Break-In of a Hunting Tooth Ratio

In order to achieve the break-in results described in the last paragraph, it is imperative to design gearsets with hunting tooth ratios. A hunting tooth condition can be established if the number of pinion or gear teeth of an integer ratio or a common denominator ratio are increased by just one tooth. Now, during the break-in every pinion tooth will mesh with every gear tooth. The influence of this kinematic difference allows the teeth to become more equal as opposed to developing their individual shapes in groups of 10 (in the above mentioned example). Figure 7 shows a single flank graphic of an 11×30 gearset after break-in. The starting condition after grinding is the same as shown in Figure 4. The single flank pattern in Figure 4 shows next to the high-frequency tooth mesh, the sine-shaped gear runout per gear revolution which is superimposed with the sinusoidally shaped pinion runout of each pinion revolution. After the break-in it can be observed in Figure 7 that the pinion runout as well as the tooth mesh ripple has reduced noticeably. Overall it can be stated that the break-in improved the transmission quality of the gearset and most likely also the gearset's quality class.

In order to visualize the different effects of a break-in and of polishing, it was possible to allocate a ground hypoid gearset which was driven in a vehicle for 300 miles. The ring gear of this set was then compared to the same size hypoid gearset, which was freshly ground and with a second one which had been super finished after grinding. These three ring gears were used for a measurement of the surface roughness in the mean tooth surface area, where the contact pattern is located. The results of this surface roughness comparison is shown in Figure 8. The top graphic in the figure shows the roughness measurement results of the ground ring gear. The center graphic in Figure 8 shows the alteration which occurred after a 300 mile break-in. The surface roughness value Ra dropped to about 50% of the original roughness. Also the value Rz dropped below 70% of the value after grinding.

The bottom graphic in Figure 8 shows the surface finish after super finishing the freshly ground ring gear. The roughness value Ra dropped to 12% of the ground pinion surface. Also the value Rz reduced significantly to only 15% of the original number.

The roughness characteristic as it is created by the break-in process has advantages for the buildup of a stable oil film with a high-load carrying properties versus the super finished gearset. It can be noticed, comparing the center and the bottom graphic in Figure 8 that the oil pockets provided by the roughness valleys have completely disappeared during the super finishing treatment. Single flank tests with slow RPM and high RPM microphone recordings also proved that the operating noise at the most critical low load conditions is lower for conventionally broken-in gearsets compared to the super finished version.

During the servicing of a gearset with a hunting tooth ratio, it is not of any use to mark a tooth and the slot it meshes with because the "tooth hunting" will put the gears back for an equally optimal performance as before removal — independent from the orientation of the gears.

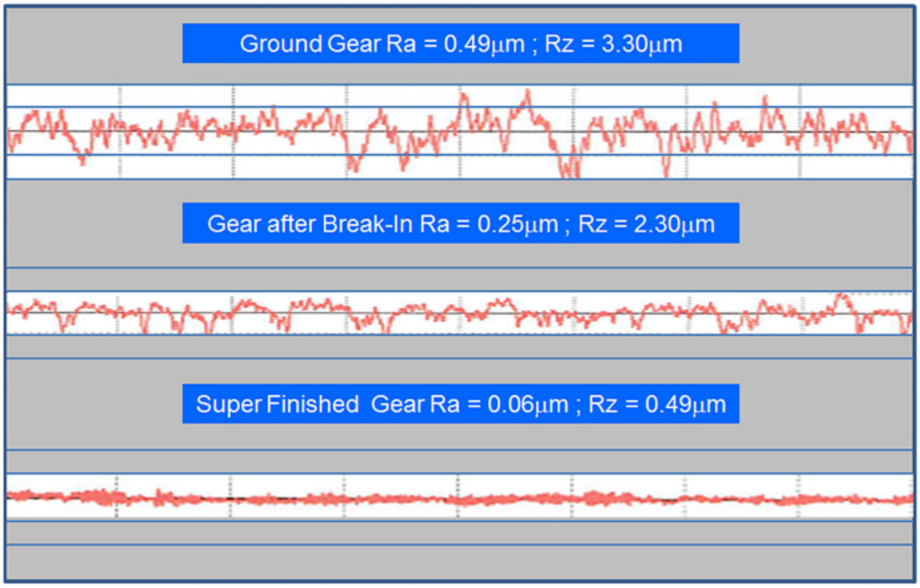

Figure 8 **Surface roughness of a ground, broken-in and super-finished flank.**

For more information.

Questions or comments regarding this paper? Contact Dr. Stadtfeld at *hstadtfeld@gleason.com.*

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Dr. Hermann J. Stadtfeld is the Vice President of Bevel Gear Technology and R&D at the Gleason Corporation and Professor of the Technical University of Ilmenau, Germany. As one of the world's most respected experts in bevel gear technology, he has published more than 300 technical papers and 10 books in this field. Likewise, he has filed international patent applications for more than 60 inventions based upon new gearing systems and gear manufacturing methods, as well as cutting tools and gear manufacturing machines. Under his leadership the world of bevel gear cutting has converted to environmentally friendly, dry machining of gears with significantly increased power density due to non-linear machine motions and new processes. Those developments also lower noise emission level and reduce energy consumption.

For 35 years, Dr. Stadtfeld has had a remarkable career within the field of bevel gear technology. Having received his Ph.D. with summa cum laude in 1987 at the Technical University in Aachen, Germany, he became the Head of Development & Engineering at Oerlikon-Bührle in Switzerland. He held a professor position at the Rochester Institute of Technology in Rochester, New York From 1992 to 1994. In 2000 as Vice President R&D he received in the name of The Gleason Works two Automotive Pace Awards — one for his high-speed dry cutting development and one for the successful development and implementation of the Universal Motion Concept (UMC). The UMC brought the conventional bevel gear geometry and its physical properties to a new level. In 2015, the Rochester Intellectual property Law Association elected Dr. Stadtfeld the "Distinguished Inventor of the Year." Between 2015–2016 CNN featured him as "Tech Hero" on a Website dedicated to technical innovators for his accomplishments regarding environmentally friendly gear manufacturing and technical advancements in gear efficiency.

Stadtfeld continues, along with his senior management position at Gleason Corporation, to mentor and advise graduate level Gleason employees, and he supervises Gleason-sponsored Master Thesis programs as professor of the Technical University of Ilmenau — thus helping to shape and ensure the future of gear technology.

NVH Analysis and Simulation of Automotive E-Axles

D. Marano, L. Pascale, J. Langhart,
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Introduction

The automotive industry is continuously developing new electrified powertrain architectures and vehicle technologies to optimize vehicle fuel consumption and reduce carbon dioxide (CO_2) and other pollutant emissions to withstand the regulations. According to the European Community (EU) statistics (Ref. 1) transportation accounts for 20% of total energy use and is responsible for around 25% of the total EU emissions of carbon dioxide, the main greenhouse gas. The European regulation 2019/631 has set a new EU fleet-wide CO_2 emission targets, as a percentage reduction starting from 2021 points: 15% reduction from 2025 on and 37.5% from 2030 on. In the USA, transportation accounts for 28% of total energy use and is responsible for 33% of total CO_2 emission. The USA national program for greenhouse gas emissions (GHG) and fuel economy standards for light-duty vehicles (passenger cars and trucks) was developed jointly by EPA and the National Highway Traffic Safety Administration (NHTSA). NHTSA and the EPA are proposing the "Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021–2026 Passenger Cars and Light Trucks" (Ref. 1). The SAFE Vehicles Rule, if finalized, will establish new standards for Corporate Average Fuel Economy (CAFE) and tailpipe Green House Gas (GHG) emission standards for passenger cars and light trucks covering model years 2021 through 2026.

Some of the main drivers of powertrain electrification are the improved efficiency of the architectures, the displacement of fossil fuel as a primary energy source, the reduced impact on the environment (at the site of utilization), and the reduced cost of fueling. The electrified vehicles architectures actually on the market can be divided in Hybrid Electric Vehicles (HEV), Plug-In Hybrid Electric Vehicles (PHEV), Battery Electric Vehicle (BEV, AEV) and Fuel Cell Electric Vehicles (FCEV).

The *HEV (hybrid electric vehicle)* vehicle carries both an internal combustion and an electric propulsion system: for space and weight reasons, the latter uses a small battery; generally, both are capable of moving the car.

The *PHEV (plug-in hybrid electric vehicle)* configuration has almost universally replaced the HEV layout from which it derives, enhancing its charging capabilities via a grid connection, typically only in AC.

In the *BEV (battery electric vehicle)* architecture, electric energy enters the vehicle as alternate current (going through an AC/DC converter) or direct current according to the type of charger. From here it goes through an inverter to be fed to the electric motor, typically AC synchronous. Wheels are also connected to a generator for the recuperation of braking energy.

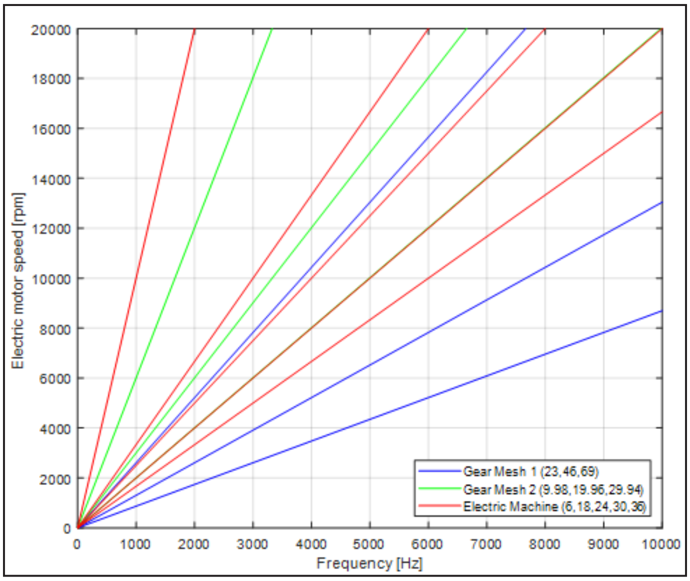

Figure 1 Campbell plot of the case study transmission.

The *FCEV (fuel cell electric vehicles)* vehicle has an electric propulsion system with the electric energy coming from the fuel cell stack where hydrogen is oxidized; such energy can be fed either directly to the electric motor or to the small battery.

The change from conventional vehicles to vehicles propelled by Electric Drive Units (EDUs) leads to a reduction in overall vehicle exterior and interior noise levels, especially during low-speed vehicle operation. Even though the radiated sound power of EV is lower than internal combustion engine (ICE) powered vehicles, the NVH behavior of such vehicles can be objectionable due to the presence of tonal noise coming from electric machines and gear train components as well as the high-frequency noise generated by the DC/AC converters. Advanced simulation of the EDU's NVH behavior in the design phase is thus critical to fulfill the vehicle NVH integration process and reduce the time to market (TTM).

Two target setting approaches for transmission and electric motor NVH are presented in (Ref. 2): the "vehicle-centric" synthesization of component level noise data to the vehicle interior (using specific or generic transfer function data) and the "component level" definition of noise targets, allowing efficient assessment of component NVH performance. Various aspects of the EDU NVH development process are qualitatively described in (Ref. 3) and the areas to be addressed during the development for optimized NVH behavior are identified concerning geartrain, electric motor, and power electronics; a state of the art regarding these topics is performed in the following.

The theory regarding the fundamentals of geartrain NVH optimization is well explained in the books of Smith (Ref. 4) and Beranek (Ref. 5). An effective literature survey of gear noise and vibration has been conducted by Akerblom (Ref. 6), concerning gear noise excitation, dynamic models, and gear noise and vibration measurement. Several studies on the nonlinear dynamics of gear transmissions, both spur, and planetary, have been conducted worldwide by research institutes such as the Gear Lab at Ohio State University (Refs. 7–10), the "Gear Research center (FZG)" at Technical University of Munich (Refs. 11–14), and Powertrain Laboratory at University of Modena and Reggio Emilia (Refs. 15–18).

The electric motor (EM) and power electronics NVH performance is a key consideration in the design of EDUs. The high-frequency noise generated by the electromagnetic force of EM and the high-frequency umbrella shape noise of DC/AD converters is subjectively quite annoying, thus many OEMs and research institutes have addressed the problem. The fundamental concepts to improve the noise performance of electrical motors at the design stage are explained in (Ref. 19). Kang has analyzed the electromagnetic noise of an EM in a pure electric car (Ref. 20), providing an effective state of the art.

This paper addresses a methodology for NVH analysis and simulation of an automotive E-axle. The theoretical calculation of a Campbell diagram including electrical and mechanical orders is presented and a constrained modal analysis of the system on mountings is performed to calculate its natural frequencies.

The electric axle is modeled as a fully flexible multibody system after having applied the Craig-Bampton modal reduction technique, whose details are discussed in this paper, to all bodies. The forced response is calculated at a constant speed of the electric motor. NVH performance of high-contact ratio gears (HCR) is evaluated with respect to standard ISO-53 gear profile A. For this purpose, peak-to-peak transmission error (PPTE), gear meshing, and bearing forces are compared for both configurations. The effect of the housing stiffness is investigated.

Housing equivalent radiated power (ERP) resulting from both ISO-53 profile A and HCR gears simulation is compared showing the reduction of surface normal velocities. The critical areas for the design of the housing are shown by means of contour plots.

E-Axle Noise and Vibration Analysis

Campbell diagram of a mechanical transmission. The Campbell diagram represents the vibration frequencies of a system at various operating speeds. A typical Campbell diagram plot is shown (Fig. 1): the system frequency is along the X-axis and the electric motor speed is along the Y-axis. This study is necessary to determine if a natural frequency is excited by running frequency or its harmonics and if orders coming from different sources overlap, which must be avoided. In the following, calculation of the excitation frequencies (also called excitation orders) of both electrical and mechanical components is presented.

Shaft unbalance and misalignment excitation orders. All rotating machines produce vibrations that typically arise from the system dynamics faults such as shaft misalignment and rotor unbalance. The ISO 1940 (Ref. 21) defines unbalance as: *"that condition, which exists in a rotor when vibratory, force or motion is imparted to its bearings as a result of centrifugal forces,"* and gives specifications for balance tolerances, and methods for verifying the residual unbalance.

For all types of unbalance, the FFT spectrum will show a predominant 1 × rpm frequency of vibration, or equivalently, an excitation order equal to 1. The vibration force produced by an unbalance mass M_u is represented by:

$$F_u = M_u \cdot r \cdot \omega^2 \sin(\omega t) \quad (1)$$

where time t is in seconds. The vibration amplitude at the 1 × rpm frequency varies proportionally to the square of the rotational speed.

Shaft misalignment, as unbalance, is a major cause of machinery vibration. There are two types of misalignment: parallel and angular misalignment. With parallel misalignment, the shaft centerlines are parallel, but they have an offset; with angular misalignment, the shaft centerline meets at an angle with each other. As explained in (Ref. 22), angular misalignment results in axial vibrations at the 1 × rpm and 2 × rpm frequency; parallel misalignment results in a 2 × rpm vibration in the radial direction that approaches a 180° phase difference across the coupling. When either angular or parallel misalignment is severe, it can generate high-amplitude peaks at higher harmonics (3× to 8×).

Gear excitation orders. The spectrum of any electric axle shows a range of frequencies related to gear mesh frequency (GMF). The fundamental gear mesh frequency f_m is calculated as the product of the number of teeth of a pinion z_1 (or a gear z_2), and its respective shaft frequency f_{s1} (f_{s2}):

$$f_m = z \cdot f_s \quad (2)$$

The amplitude of the gear meshing frequency is usually related to the transmitted load, thus vibration analysis of the e-axle should be conducted at the maximum power. Sidebands

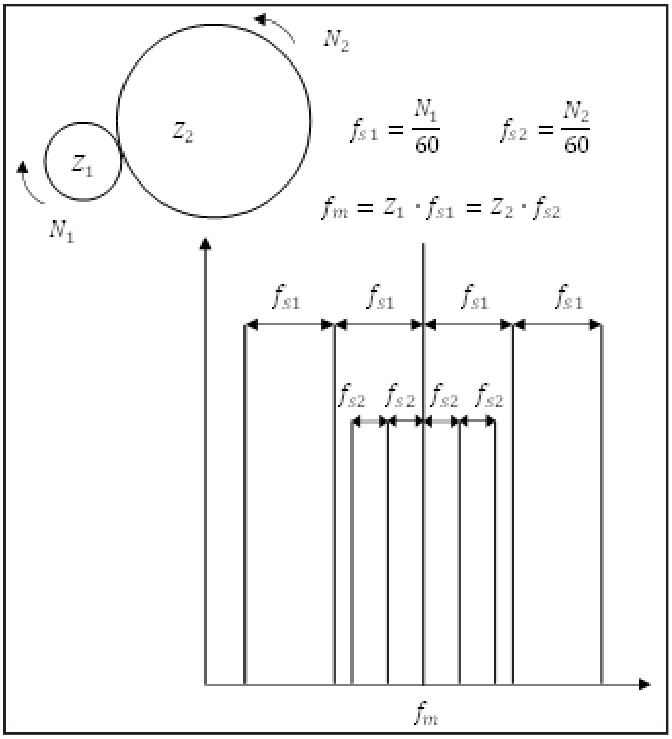

Figure 2 Gear mesh frequency.

around the gear mesh frequency, having a frequency $f_m \pm$ the shafts rotational frequencies f_{s1}, f_{s2} and its harmonics are quite common due to gear faults such as wear, defects, misalignment, and eccentricity. A description of sidebands related to gearing defects is presented in (Ref. 22).

In automotive e-axles, epicyclic gearboxes are often used due to the high-power density. In epicyclic systems, planet gears are mounted on a movable carrier revolving about a central gear with a fixed axis (Fig. 3). For the simple case where the sun gear represents the input and the carrier the output, with the ring gear fixed, the fundamental mesh frequency is calculated as:

$$f_m = z_r \cdot \frac{n_c}{60} = \frac{z_r \cdot z_s}{z_r + z_s} = \frac{n_s}{60} \tag{3}$$

Where z_r and z_s are, respectively, the ring gear and sun gear number of teeth, n_c and n_s are respectively the carrier and the sun shaft rotational speeds.

An analysis of sidebands for epicyclic gearbox can be found, e.g., in (Refs. 23–24). Different combinations of input/output or more complex schemes are described in ANSI/AGMA 6123-C16 (Ref. 25).

Bearings excitation orders. The vibrations related to the bearings can be either tonal or broadband. Tonal vibrations in new bearings are generally caused by production imperfections (Ref. 23), including, but not limited to, the cases when the stiffness of both inner and outer rings is not ideal and they get ovalized due to the clamping for grinding. Broadband vibrations originate from the defects of raceways and rolling elements imperfections; a smooth operation is thus expected when bearings are new. The SKF company has published a comprehensive analysis of bearing damage and failure modes (Ref. 26), and a guide to the interpretation of vibration signals (Refs. 27–28). In the following, calculation of the main bearing defect frequencies is presented as a function of the ball bearing dimensions and other bearings' geometric parameters (Table 1).

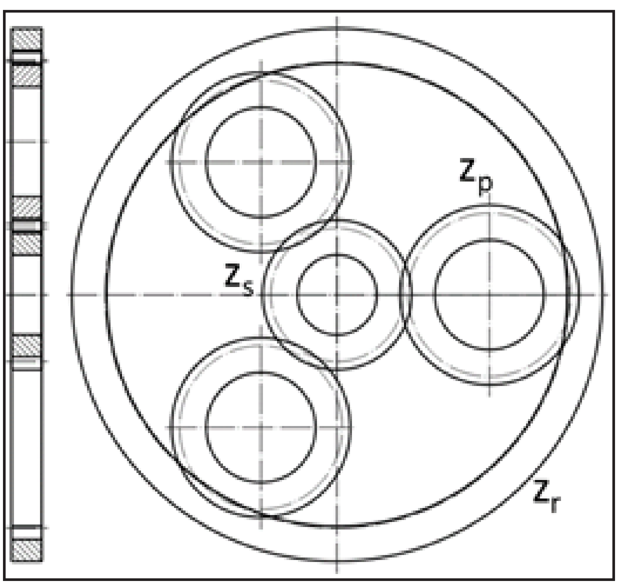

Figure 3 **An epicyclic gearbox.**

Table 1 Bearing geometric parameters	
Outer diameter	D_1
Bore diameter	D_2
Pitch diameter	$PD \cong \frac{D_1+D_2}{2}$
Rolling element diameter	D_b
Contact angle	β
Number of rolling elements	n
Revolutions per second (or relative speed difference between outer and inner race)	rps

Fundamental train frequency (FTF)

The fundamental train frequency is related to defects affecting the rotation of the cage; the rotational frequency of the bearing cage may be calculated as:

$$f_{FTF} = \frac{rps}{2} \cdot \left(1 - \frac{D_b}{PD} \cdot \cos\beta\right) \tag{4}$$

Ball pass frequency of the outer race (BPFO)

The ball pass frequency of the outer race is the frequency of the rolling elements passing by a defect located on the outer raceway; it can be calculated as:

$$f_{BPFO} = \frac{n \cdot rps}{2} \cdot \left(1 - \frac{D_b}{PD} \cdot \cos\beta\right) \tag{5}$$

Ball pass frequency of the inner race (BPFI)

The ball pass frequency of the inner race is the frequency of the rolling elements passing by a defect located on the inner raceway; it can be calculated as:

$$f_{BPFI} = \frac{n \cdot rps}{2} \cdot \left(1 + \frac{D_b}{PD} \cdot \cos\beta\right) \tag{6}$$

Ball-spin/roller frequency (BSF)

The ball-spin/roller frequency is the frequency related to the impacts of the rolling element with either the inner or the outer race; it can be calculated as:

$$f_{BSF} = \frac{n \cdot rps}{2 \cdot D_b} \cdot \left[1 - \left(\frac{D_b}{PD} \cos\beta\right)^2\right] \tag{7}$$

Electric machine excitation orders. The noise of an electric motor is caused by the electromagnetic force in the air gap, exciting the stator and the motor casing. The electromagnetic force can be decomposed in a tangential force, generating the e-motor torque, and a radial force responsible for the e-motor noise which does not affect the operation of the e-motor. The electromagnetic excitation force is influenced by the design parameters of the electric motor, such as the motor topology (number of poles and slots), the shape of the poles and slots, the shape of the current, and several other parameters. Based on the theoretical calculation formulas reported in (Ref. 20), the frequency characteristics and spatial order characteristics of the electromagnetic radial force of a permanent magnet synchronous motor are obtained (Ref. 29). Table 2 lists the main electromagnetic frequencies f_m. where p is the number of pole pairs, s is the number of stator slots, f is the motor rotational frequency in Hz, k=0,1,2,3…, k_1=0,1,2,3…, n=6k±1).

Excitation orders of the case study e-axle. The electric axle

Table 2 Main electric motor frequencies of radial force wave in synchronous motors	
Product of the stator spatial harmonics of the same number	$f_1=2pnf$
Product of the rotor spatial harmonics of the same number	$f_2=2pn(1\pm 2k_1)f$
Product of the stator winding and rotor spatial harmonics	$f_3=2pn(1+k_1)f$ and $f_3=2pnk_1 f$
Interaction of the rotor magnetic field and the slotted core of the stator	$f_4=p\mu_\lambda f$ where $\mu_\lambda=int\left[\frac{ks}{p}\right]$

Table 3 Gears data and meshing orders for the LCR and HCR gears

Gear Parameters		I stage		II stage	
		Gear 1	Gear 2	Gear 3	Gear 4
Number of teeth	z [-]	23	53	23	89
Helix angle at reference circle	β [°]	30		15	
Normal pressure angle	αn [°]	20		20	
Normal module	mn [mm]	2.5		2.6	
Profile shift coefficient	x^* [-]	0.0163	-0.6682	0.4706	-0.6659
Face width	b [mm]	25	23	40	38
Center distance	a [mm]	107.99		150.22	
Gear Mesh Excitation order	GMF	23.00		9.98	
Gear profile LCR	$h^*_{fP}/\rho^*_{fP}/h^*_{aP}$	1.25/0.38/1.00	1.25/0.38/1.00	1.25/0.38/1.00	1.25/0.38/1.00
Gear profile HCR	$h^*_{fP}/\rho^*_{fP}/h^*_{aP}$	1.80/0.19/1.35	1.60/0.29/1.60	1.60/0.29/1.35	1.60/0.29/1.45
Transverse contact ratio LCR	ε_α [-]	1.43		1.53	
Transverse contact ratio HCR		2.05		2.10	
Overlap ratio	ε_β [-]	1.46		1.20	

Table 4 Bearings dimensions and excitation orders

Bearing	Type	D_1 [mm]	D_2 [mm]	n [mm]	PD [mm]	D_b [mm]	n [-]	β [°]	FTF	BPFO	BPFI	BSF
b1 – EM rotor	Ball Bearing	50	90	20	70.00	12.7	10	0	0.41	4.09	5.91	2.67
b2 – EM rotor	Ball Bearing	50	110	27	80.00	19.1	8	0	0.38	3.05	4.95	1.98
B1 – Input (EM side)	Ball Bearing	45	85	19	65.00	12.3	10	0	0.41	4.05	5.95	2.55
B2 – Input	Ball Bearing	45	85	19	65.00	12.3	10	0	0.41	4.05	5.95	2.55
B3 – Intermediate	Ball Bearing	50	90	20	70.00	12.7	10	0	0.18	1.77	2.55	1.15
B4 – Intermediate	Ball Bearing	50	90	20	70.00	12.7	10	0	0.18	1.77	2.55	1.15
B5 – Output	Taper roller bearing	80	110	20	94.67	7.4	34	NA	-	-	-	-
B6 – Output	Taper roller bearing	80	110	20	94.67	7.4	34	NA	-	-	-	-

analyzed in the following is a single-speed, two-stage gearbox powering the front wheels of an electric vehicle (Fig. 4).

Power is supplied by a permanent magnet synchronous motor to the input shaft, through a spline connection. The electric machine has $2p=6$ poles and $s=36$ stator slots. The output gear stage is integral to the differential case. The modeling of the differential stage is not considered in the present paper.

Table 3 reports gears macrogeometry data for two designs — low-contact ratio (LCR) gears and high-contact ratio (HCR) gears — with a transverse contact ratio $\varepsilon_\alpha>2$. For both designs, first-stage gear mesh order is 23.00 and the second-stage gear mesh order is 9.98; order 1 is referred to electric machine shaft.

Table 4 shows bearings selection for the electric axle, and main excitation orders. For the bearings of the intermediate and output shafts, calculated orders are divided by 53/23 and 53/2389/23 respectively, in order to report them to the electric machine.

In Table 5 main calculated electric machine orders are reported. A practical design rule is to avoid overlapping multiples of the number of poles with gear mesh orders (distance between orders should be at least 3%). On the case study electric axle, however, electric machine order 24 is very close to the first-stage gear mesh order, 23, and the third harmonic of the second-stage gear mesh order, 9.98, matches the electric machine order 30 (Fig. 1).

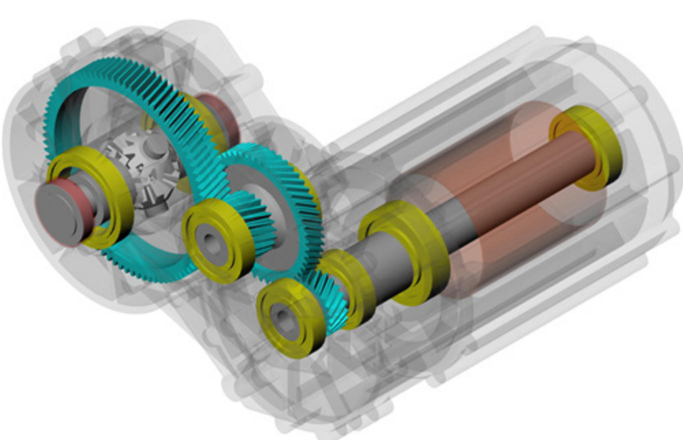

Figure 4 E-axle layout in KISSsys.

Table 5 Electric motor excitation frequencies

Product of the stator spatial harmonics of the same number	6, 30, 42, …
Product of the rotor spatial harmonics of the same number	6, 18, 30, 42, …
Product of the stator winding and rotor spatial harmonics	6, 12, 18, 24, 30, 36, 42, …
Interaction of the rotor magnetic field and the slotted core of the stator	36, 72, …

Multibody simulation approach. Dynamic response of the electric axle to the inputs such as electric machine torque (mean and ripple torque), presence of unbalanced forces, misalignments etc. has to be evaluated in order to predict the displacement and acceleration levels on the housing and noise emission.

- To this purpose, multibody tools are adopted where each body is representative of a certain substructure. Considering the case of an electric axle, one might consider the following bodies:
- Housing with its supports, the outer cages of bearings, the stator of the electric machine
- Rotor of the electric machine
- Each rotating shaft with gears and inner cages of supporting bearings

Then, connections between bodies through joints must be set up. General joints (force-displacement and force-velocity laws) can be used to model spline connections and the presence of mountings; specific joints should be adopted to model gears (shaft-shaft) and bearings (shaft-housing) connections.

According to multi-body theory, the displacement field of each substructure is described with a linear combination of suitable shape functions (i.e. — modes). The size of the numerical problem can be significantly reduced if only shape functions related to the frequency range of interest are considered (Ref. 30).

Modal analysis. Modal analysis is the process of determining the dynamic characteristics of a system in forms of natural frequencies, damping factors, and mode shapes and using them to formulate a mathematical model to describe its dynamic behavior (Ref. 31). Free vibrations of an MDOF $\{x\}$ system can be studied, starting from its undamped equation of motion:

$$[M]\{\ddot{x}\}+[K]\{x\}=\{0\} \tag{8}$$

where $\{r\}$ is the mass matrix, usually positive definite, is the stiffness matrix which is semi-positive definite in case the system shows rigid body modes (as in the case of an electric axle on its mountings). The non-trivial solution of Equation 8 provides the free vibration of the system. Imposing a type of motion for which all Lagrangian coordinates depend on the same time function, i.e. $\{x\}=\{\phi\}\sin(\omega t)$, leads to:

$$(-\omega^2[M]\{\ddot{x}\}+[K])\{\phi\}=\{0\} \tag{9}$$

Non-trivial solutions are those for which the matrix $(-\omega^2[M]+[K])$ is singular:

$$\det(-\omega^2[M]\{\ddot{x}\}+[K])=\{0\} \tag{10}$$

Equation 10 represents an Eigenvalue problem, where ω^2 is the Eigenvalue (the square of the natural frequency of the system) and $\{\phi\}$ is the Eigenvector (the mode shape).

Electric axles are supported by mountings, whose main purpose is to isolate the disturbance coming from the system itself from the vehicle structure. To determine the six low-frequency rigid modes the mass matrix assumes the following form:

$$[M]=\begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & J_{xx} & -J_{xy} & -J_{xz} \\ 0 & 0 & 0 & -J_{yx} & J_{yy} & -J_{yz} \\ 0 & 0 & 0 & -J_{zx} & -J_{zy} & J_{zz} \end{bmatrix} \tag{11}$$

where m is the total mass of the system and J_{ij} represents the components of the mass moment of inertia tensor around each axis. The stiffness matrix depends on mountings characteristics in terms of static and dynamic stiffness (Ref. 32).

The first flexible modes usually encountered for an electric axle are related to the bending modes of the supports which connect the housing to the mountings. These modes can lead to NVH disturbances for the driver if they propagate towards the vehicle structure interacting with other dynamic systems in a certain frequency band; i.e. — in a certain range of vehicle speed.

To overcome issues of this type, it might be necessary to increase the supports stiffness-to-mass ratio corresponding to the disturbing mode to exit the interest frequency band or to reduce vibration; for example, by utilizing a tuned mass damper.

Other potential sources of noise are membrane modes of the housing or of other components mounted on it, such as the inverter. So, in the design phase, apart from strength calculation also modal characteristics of the system must be considered in order to avoid NVH issues.

Modal reduction techniques.In structural dynamics, finite element models are adopted to represent the dynamic behavior of a substructure. These models are often too refined and have millions of DOFs, therefore solving dynamic problems may result in unfeasible computation times. Thus, component model reduction methods are adopted, whose idea is modal superposition, i.e. — nodal displacements are written as a linear combination of normal modes $\{\phi_j\}$ and modal amplitudes η_j:

$$\{x\}=\textstyle\sum_{j=1}^{m}\{\phi_j\}\eta_j \tag{12}$$

The general form of the equations of motion for each substructure reads:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{p\}+\{g\} \tag{13}$$

where $[M]$is the substructure mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix and $\{p\}+\{g\}$ is the force vector; $\{p\}$ denotes the externally applied forces and $\{g\}$ the forces coming from the neighboring substructures. The reduction is performed transforming the set of original DOFs $\{x\}$ into a set of generalized DOFs $\{q\}$ via the transformation matrix $[R]$:

$$\{x\}=[R]\{q\} \tag{14}$$

$[R]$ is the reduction basis, whose dimensions are $n\times r$. The reduced set of DOFs (r) should be small with respect to the original set of DOFs (n), for an efficient reduction.

Substituting Equation (14) into Equation (13) leads to:

$$[M][R]\{\ddot{q}\}+[C][R]\{\dot{q}\}+[K][R]\{q\}=\{p\}+\{g\}+\{r\} \tag{15}$$

where $\{r\}$ is the error arising from the fact that the reduced set of DOFs does not span the full solution space. An error is only allowed in the space not spanned by the reduction basis, i.e. $[R]^T\{r\}=0$. The projection of Equation (15) onto the reduction basis gives:

$$[R]^T[M][R]\{\ddot{q}\}+[R]^T[C][R]\{\dot{q}\}+[R]^T[K][R]\{q\}=[R]^T\{p\}+[R]^T\{g\} \tag{16}$$

i.e.:

$$[\widetilde{M}]\{\ddot{q}\}+[\widetilde{C}]\{\dot{q}\}+[\widetilde{K}]\{q\}=\{\widetilde{p}\}+\{\widetilde{g}\} \tag{17}$$

Generally, a basis is built from a set of vibration modes, which contain information of the substructure's dynamic behavior, and a set of static modes, which represent the static deformation caused by neighboring substructures (Ref. 33).

The Craig-Bampton method. In the Craig-Bampton method (Ref. 34) the substructure DOFs are divided into boundary and interface DOFs, each of them referring to a specific node-set in the finite element model:

The vibrational information is the set of fixed-interface vibration modes; the substructure is fixed at its boundary DOFs and analysis is done to obtain the Eigenmodes.

Constraint modes are used to represent the static deformation of a substructure caused by neighboring substructures.

Fixed-interface vibration modes can be computed by constraining the boundary DOFs. The first step is the partitioning of DOFs into the boundary $\{x_b\}$ and internal $\{x_i\}$. By neglecting the damping, Equation (13) can be written as:

$$\begin{bmatrix} [M_{bb}] & [M_{bi}] \\ [M_{ib}] & [M_{ii}] \end{bmatrix}\begin{Bmatrix} \{\ddot{x}_b\} \\ \{\ddot{x}_i\} \end{Bmatrix}+\begin{Bmatrix} [K_{bb}] & [K_{bi}] \\ [K_{ib}] & [K_{ii}] \end{Bmatrix}+\begin{Bmatrix} \{p_b\}+\{g_b\} \\ \{0\} \end{Bmatrix} \tag{18}$$

where $\{g_b\}$ contains the reaction forces with neighboring substructures. Constraining the boundary DOFs ($\{x_b\}=\{0\}$) leads to:

$$[M_{ii}]\{\ddot{x}_i\}+[K_{ii}]\{x_i\}=\{0\} \tag{19}$$

That can be solved as an Eigenvalue problem:

$$(-\omega_{i,j}^2[M_{ii}]+[K_{ii}])\{\phi_{i,j}\}=\{0\} \tag{20}$$

The result is the set of Eigenmodes and Eigenfrequencies of the substructure constrained at its boundary DOFs (fixed-interface vibration modes):

$$\{x_i\}=[\phi_i]\{\eta_i\} \tag{21}$$

Constraint modes contain the substructure static response to an applied boundary displacement. They are in fact representative of the static deformation due to a unit displacement applied to one of the boundary DOFs, while the remaining boundary DOFs are restrained, and no forces are applied to the internal DOFs.

The first step is again partitioning of the DOFs into the boundary and internal, which leads to Equation (18). The second equation, neglecting the inertia forces, reads:

$$[K_{ib}]\{x_b\}+[K_{ii}]\{x_i\}=\{0\} \tag{22}$$

From which:

$$\{x_i\}=-[K_{ii}]^{-1}[K_{ib}]\{x_b\} \tag{23}$$

The columns of the static condensation matrix $-[K_{ii}]^{-1}[K_{ib}]$ contain the static modes, which represent the static response of the internal DOFs $\{x_i\}$ for a unit displacement of the boundary DOFs $\{x_b\}$.

The original set of DOFs can thus be reduced to a set of boundary DOFs, as:

$$\begin{Bmatrix} x_b \\ x_i \end{Bmatrix}=\begin{bmatrix} [I] \\ -[K_{ii}]^{-1}\,[K_{ib}] \end{bmatrix}\{x_b\}=\begin{bmatrix} [I] \\ [\psi_{C,i}] \end{bmatrix}\{x_b\}=[\psi_C]\{x_b\} \tag{24}$$

Once constraint modes and fixed-interface vibration modes have been obtained, the displacement field $\{x_b\}$ of the interface nodes can be written through the superposition of the static and dynamic modes, and it is a function of the displacement field of the boundary nodes only; this is a crucial point of every condensation method:

$$\{x_i\}=[\psi_{C,i}]\{x_b\}+[\phi_i]\{\eta_i\} \tag{25}$$

The reduction basis therefore yields:

$$\begin{Bmatrix} x_b \\ x_i \end{Bmatrix}=\begin{Bmatrix} \{x_b\} \\ [\psi_{C,i}]\{x_b\}+[\phi_i]\{\eta_i\} \end{Bmatrix}=\begin{bmatrix} [I] & [0] \\ [\psi_{C,i}] & [\phi_i] \end{bmatrix}\begin{Bmatrix} \{x_b\} \\ \{\eta_i\} \end{Bmatrix}=[R_{CB}]\begin{Bmatrix} \{x_b\} \\ \{\eta_i\} \end{Bmatrix} \tag{26}$$

Finally, $[\tilde{M}]=[R_{CB}]^T[M][R_{CB}]$ and $[\tilde{K}]=[R_{CB}]^T[K][R_{CB}]$.

The generalized DOFs vector contains both physical displacements of the boundary nodes $\{x_b\}$ and modal coordinates $\{n_i\}$.

The first advantage of the Craig-Bampton method is the fact that both the constraint modes and the fixed-interface vibration

Table 6 Microgeometry modifications for LCR gearset

Microgeometry modifications [] - LCR	I stage		II stage	
	Gear 1	Gear 2	Gear 3	Gear 4
Flank crowning	10	-	3	-
Helix angle modification	-5	-	-3	-
Tip relief (Long)	15 (d_{Ca}=67.78 mm)	15 (d_{Ca}=151.59 mm)	15 (d_{Ca}=62.29 mm)	12 (d_{Ca}=235.96 mm)
Profile crowning	3	-	-	-
Pressure angle modification	-2	-	-4	-

Table 7 Microgeometry modifications for HCR gearset

Microgeometry modifications [] - HCR	I stage		II stage	
	Gear 1	Gear 2	Gear 3	Gear 4
Flank crowning	8	-	10	-
Helix angle modification	-5	-	-2	-2
Tip relief (Long)	14 (d_{Ca}=67.02 mm)	14 (d_{Ca}=150.60 mm)	15 (d_{Ca}=62.75 mm)	15 (d_{Ca}=238.50 mm)
Profile crowning	-	-	-	-
Pressure angle modification	-	-	-5	-

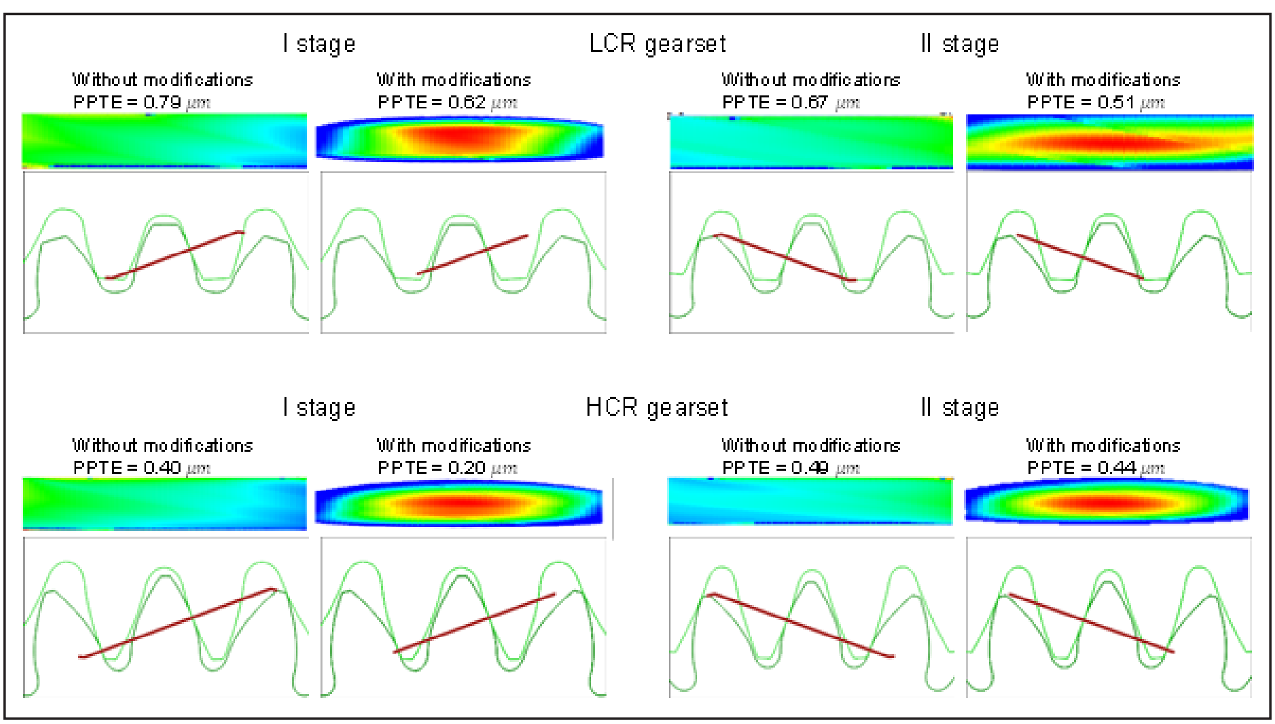

Figure 5 Effect of modifications on the contact pattern and static PPTE calculated in KISSsoft.

modes can be easily computed. Then, in the reduced system, the original boundary DOFs are retained, allowing to add or replace substructures without having to analyze again the full model. In fact, the system's substructures are connected with joints at the boundary nodes.

E-axle noise and vibration simulation. The simulations are carried out for performance improvement evaluation of the HCR gears with respect to the LCR gears regarding the peak-to-peak transmission error (PPTE), gear meshing, and bearing forces. Housing equivalent radiated power (ERP) resulting from HCR gear simulation is analyzed. Gear microgeometry modifications (Tables 1 and 2) have been designed with the help of *KISSsys*: helix angle modification and crowning have been adopted to reduce the face load factor $K_{H\beta}$, while tip relief and profile crowning have been adopted to eliminate contact shock and reduce the PPTE. Details on the methodology to design gear microgeometry are reported in (Ref. 35).

Table 8 E-axle modes of vibration

Frequency [Hz]			
Mode 1	238	Mode 6	487
Mode 2	273	Mode 7	577
Mode 3	296	Mode 8	589
Mode 4	387	Mode 9	639
Mode 5	412	Mode 10	719

The following results are obtained for an input torque of 60 nm (nearly 50% of the rated torque) at 1,000 rpm.

Constrained modal analysis. Constrained modal analysis of the E-axle on its mountings has been performed to evaluate the system's natural frequencies. Firstly, ten eigenfrequencies are listed in Table 3.

The scope of this analysis is to predict the interaction of the main excitation orders with the system natural modes. In Figure 6, an extended Campbell diagram is shown, reporting the main excitation orders together with the system eigenfrequencies and the electric motor speed adopted for the multibody simulations (1,000 rpm). When these frequencies intersect the excitation orders, an amplification of the response is expected.

Forced response analysis. The forced response analysis is performed using *Recurdyn* a multi-body dynamics (*MBD*) software, importing gears data from a *KISSsys* model. Four simulations have been performed according to the following scheme:

1. LCR and HCR gearset, rigid housing
2. LCR and HCR gearset, flexible housing

LCR and HCR gearset – rigid housing. To better understand the effect of a higher transverse contact ratio on the dynamic transmission error and gear meshing force (thus on dynamic forces loading the bearings), the first simulation is carried out with rigid housing; the main excitation orders are as follows (Fig. 1):

- Orders 23 and 46: respectively, first and second harmonics of the gear mesh frequency for the first stage.
- Orders 10, 20 and 30: respectively, first, second and third harmonic of the gear mesh frequency for the second stage.

In Figure 7, the dynamic transmission error is plotted for both the gear stages. Furthermore, the harmonic spectrum of the

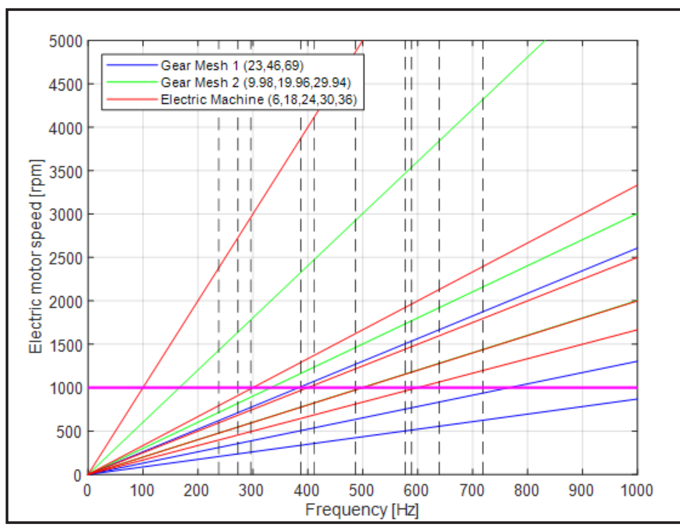

Figure 6 Extended Campbell plot including system Eigen frequencies and EM speed adopted for the multibody simulations.

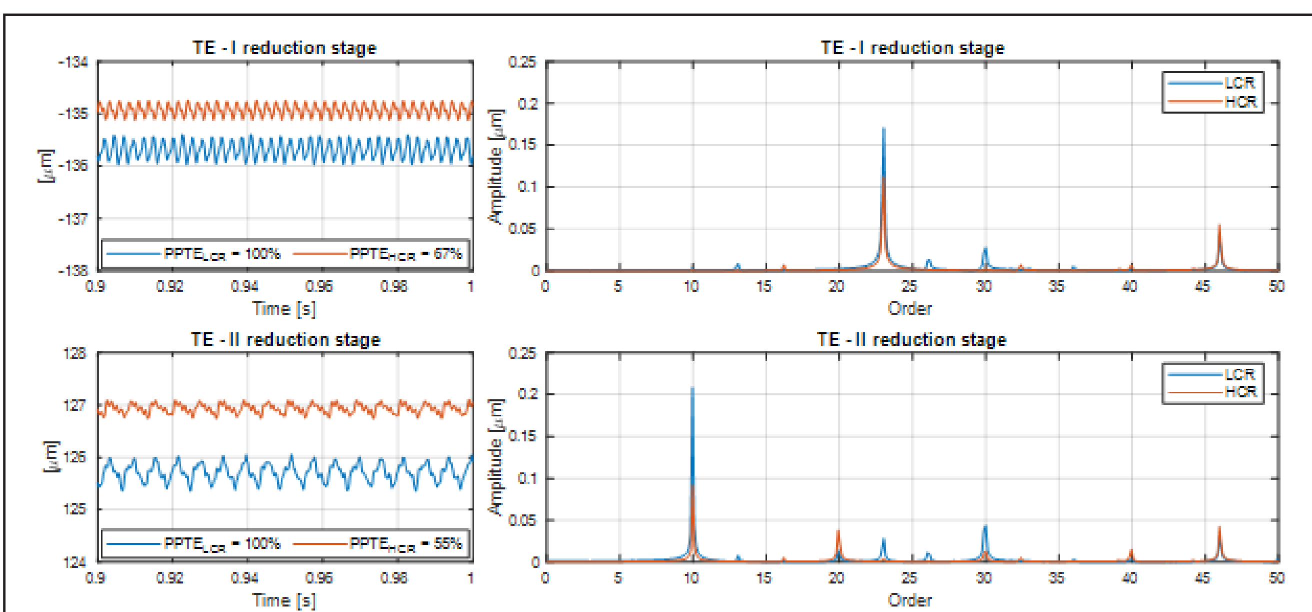

Figure 7 Transmission error and its harmonic content.

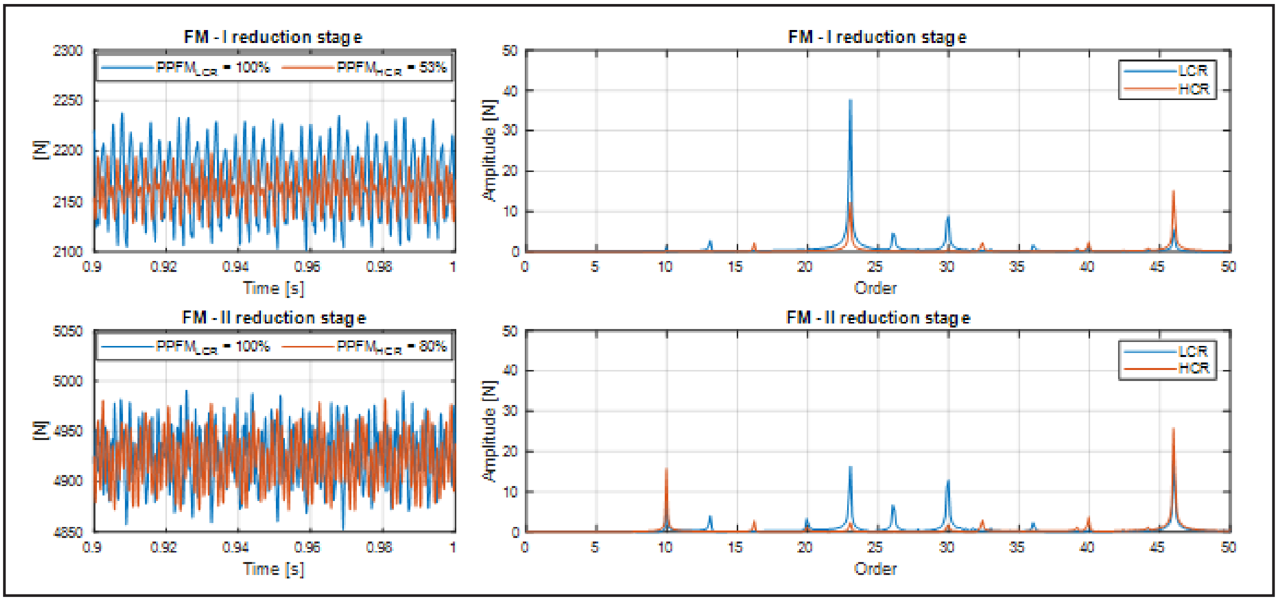

Figure 8 Gear meshing force and its harmonic content.

signal is analyzed. Results confirm a significant reduction in the amplitudes of the meshing orders for both the first and second stages of the transmission.

In Figure 8, gear meshing forces are plotted and their harmonic content is analyzed. For the first drop, the dominant orders are the ones related to the gear meshing frequencies of the first reduction stage; for the second drop, apart from order 10 and its harmonics, the presence of order 23 is especially remarkable for the LCR gearset.

In Figure 10, transmission bearing forces are compared, and the signal spectrum is shown. Since the bearings transmit the dynamic load to the housing, a reduction of the harmonic content of the bearing forces leads to a reduction in the housing excitation, which eventually results in an overall noise level reduction; bearings are named according to Figure 9.

For all bearings, the force peak-to-peak has decreased, as well, most of the harmonics have been reduced by substituting the

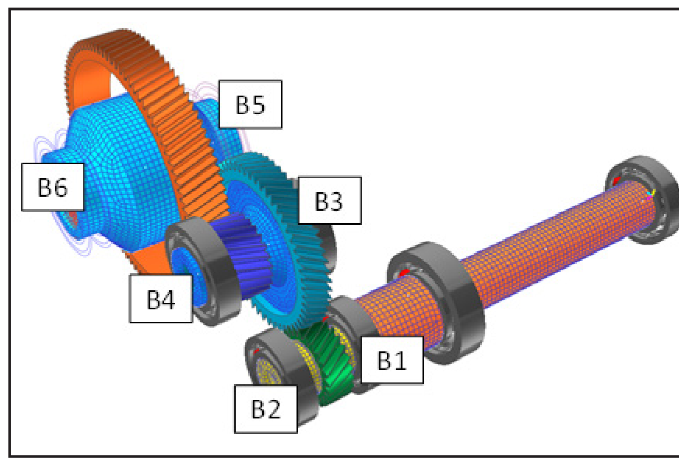

Figure 9 Transmission bearings layout in ***Recurdyn***.

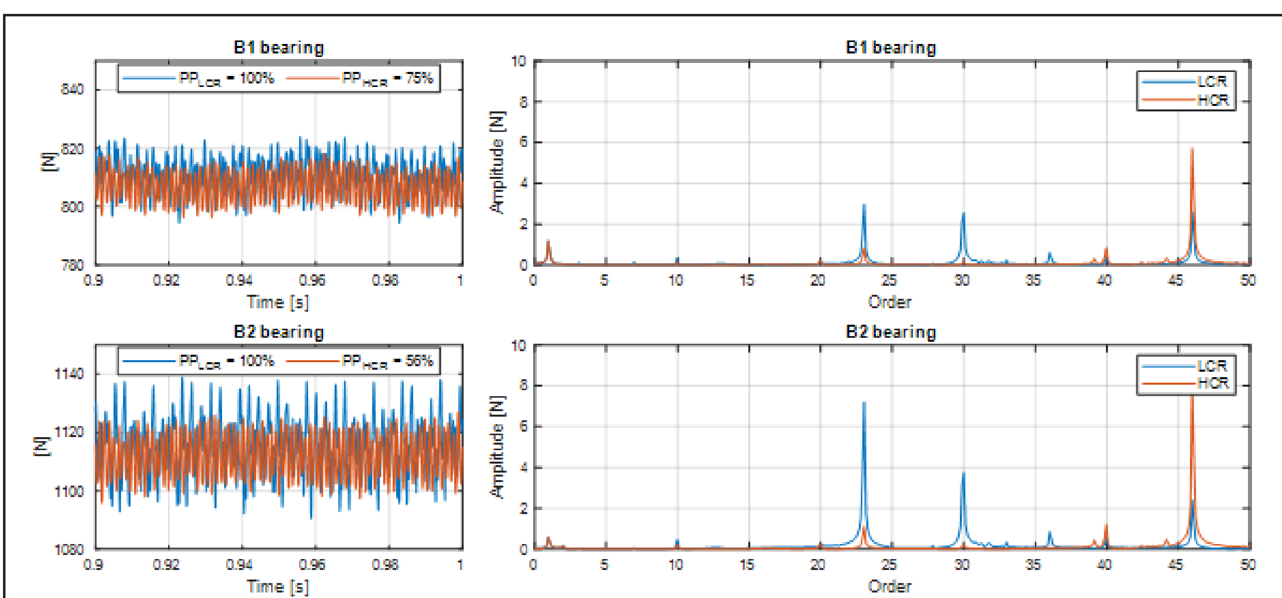

Figure 10 Bearings forces FM.

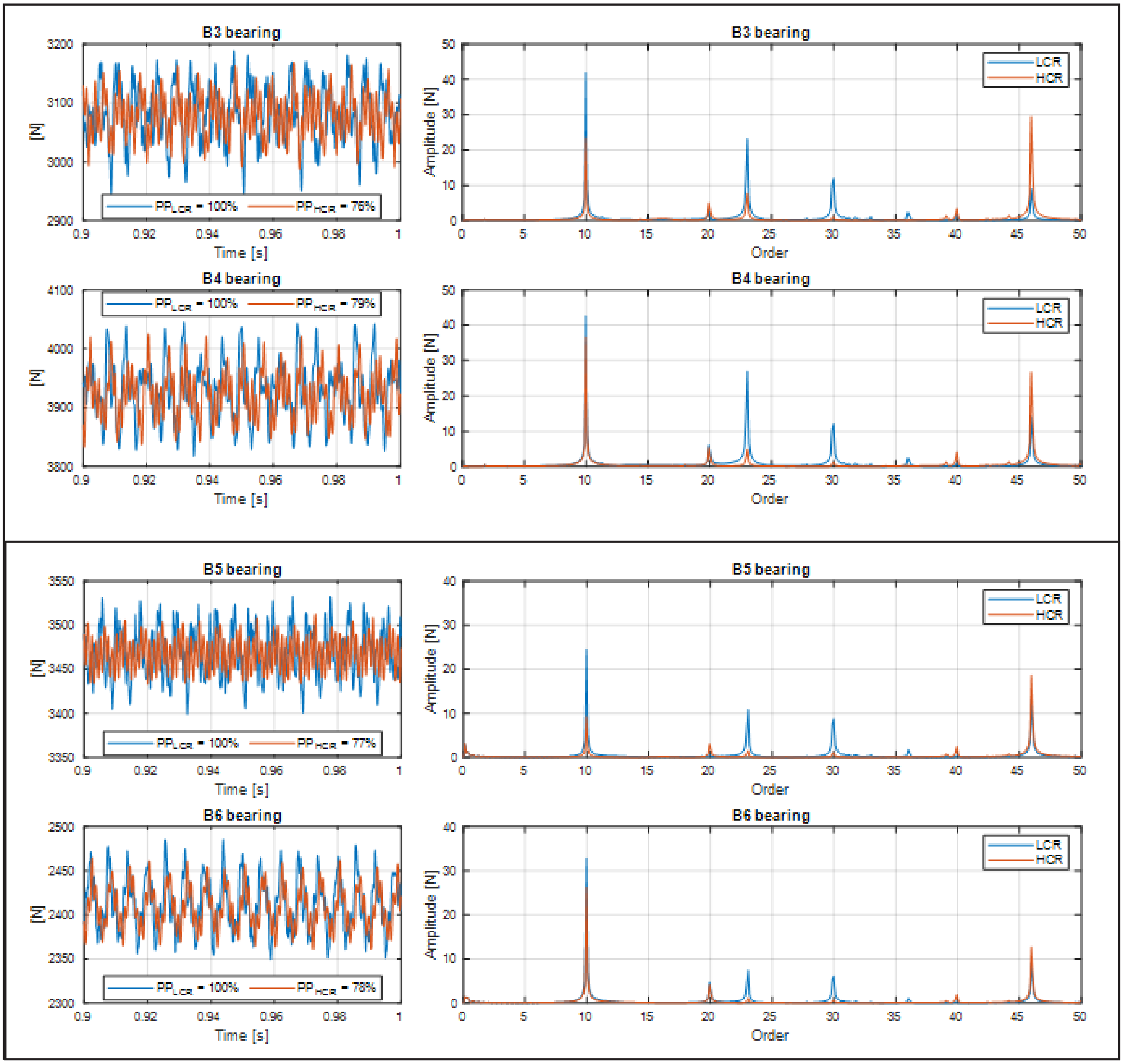

Figure 10 Bearings forces FM. (con't)

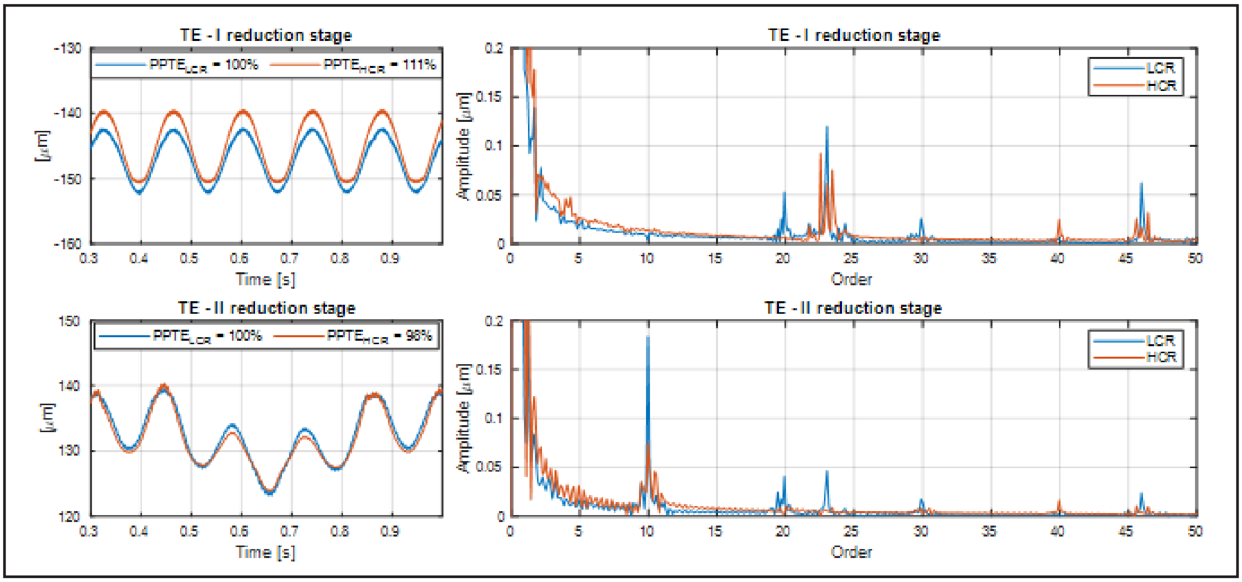

Figure 11 Transmission error and its harmonic content – flexible housing.

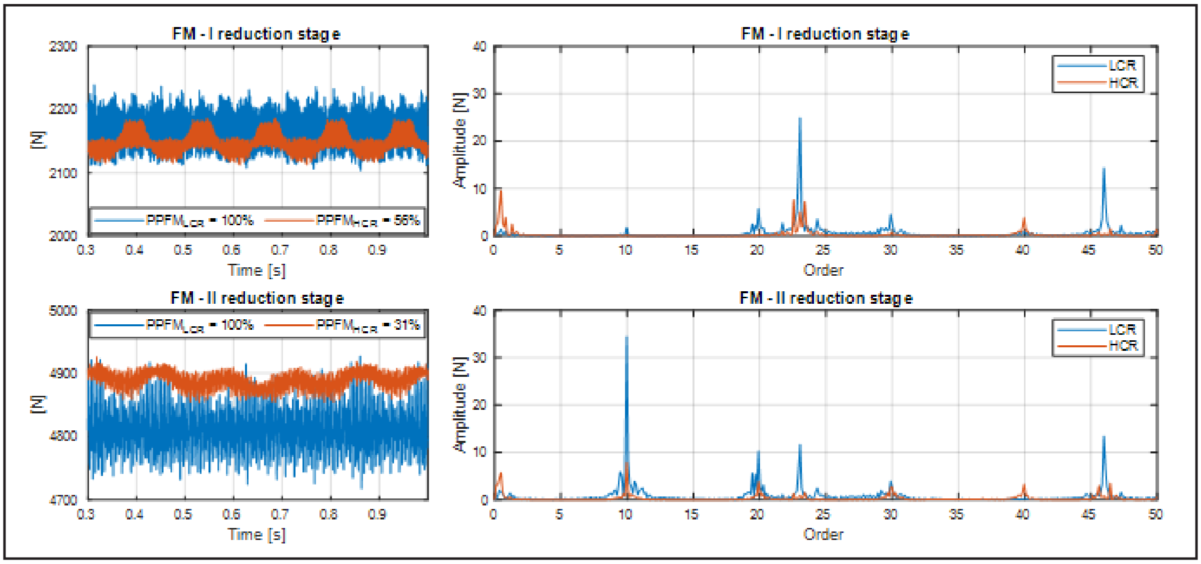

Figure 12 **Gear meshing force and its harmonic content – flexible housing.**

LCR gearset with the HCR gearset. For bearings B1 and B2 on the input shaft, main orders are related to the first-stage gear meshing frequency and its harmonics. For bearings B3 and B4 on the intermediate shaft, GMFs of both first- and second-stages are present. For bearings B5 and B6 on the output shaft, main orders are related to second-stage gear meshing frequency and its harmonics.

LCR vs. HCR – flexible housing. In the following, the results of multi-body simulation with flexible housing are shown. The transmission error is plotted (Fig. 11) for both gear stages and in both time and frequency domains. Regarding gear meshing orders, as expected, the HCR gearset has a lower TE amplitude compared to the LCR gearset. Sidebands appear because the gear meshing frequency is modulated by shaft rotational orders (as previously explained). Shaft rotational orders, calculated by means of the reduction ratios of both gear stages, are respectively 1 for the input shaft, 0.48 for the intermediate shaft and 0.11 for the output shaft. The amplitude of the orders is remarkably similar between the LCR and HCR gearsets, since it is mainly due to the presence of misalignments and runout induced by different bearing clearances.

Gear meshing forces are shown (Fig. 12) confirming a significant reduction of the harmonic content for the HCR gearset compared to the LCR gearset.

Figure 13 shows bearing forces together with signal spectrum. The comparison among the LCR and HCR gearset shows a remarkable improvement on bearing forces, and consequently, amplitude of the signal harmonics is substantially reduced.

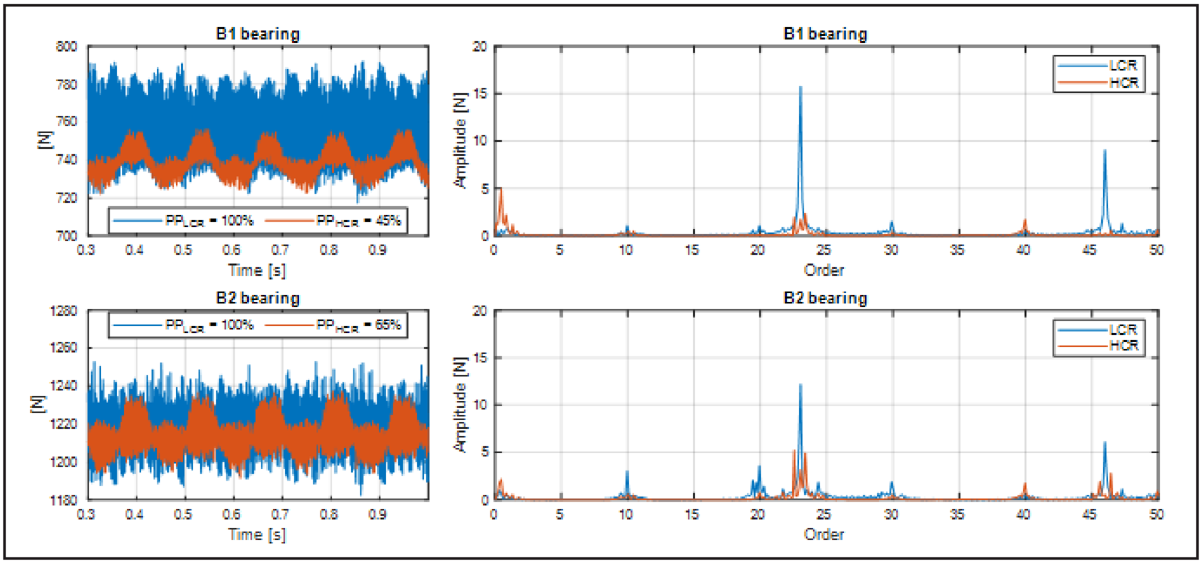

Figure 13 **Bearings forces FM – flexible housing.**

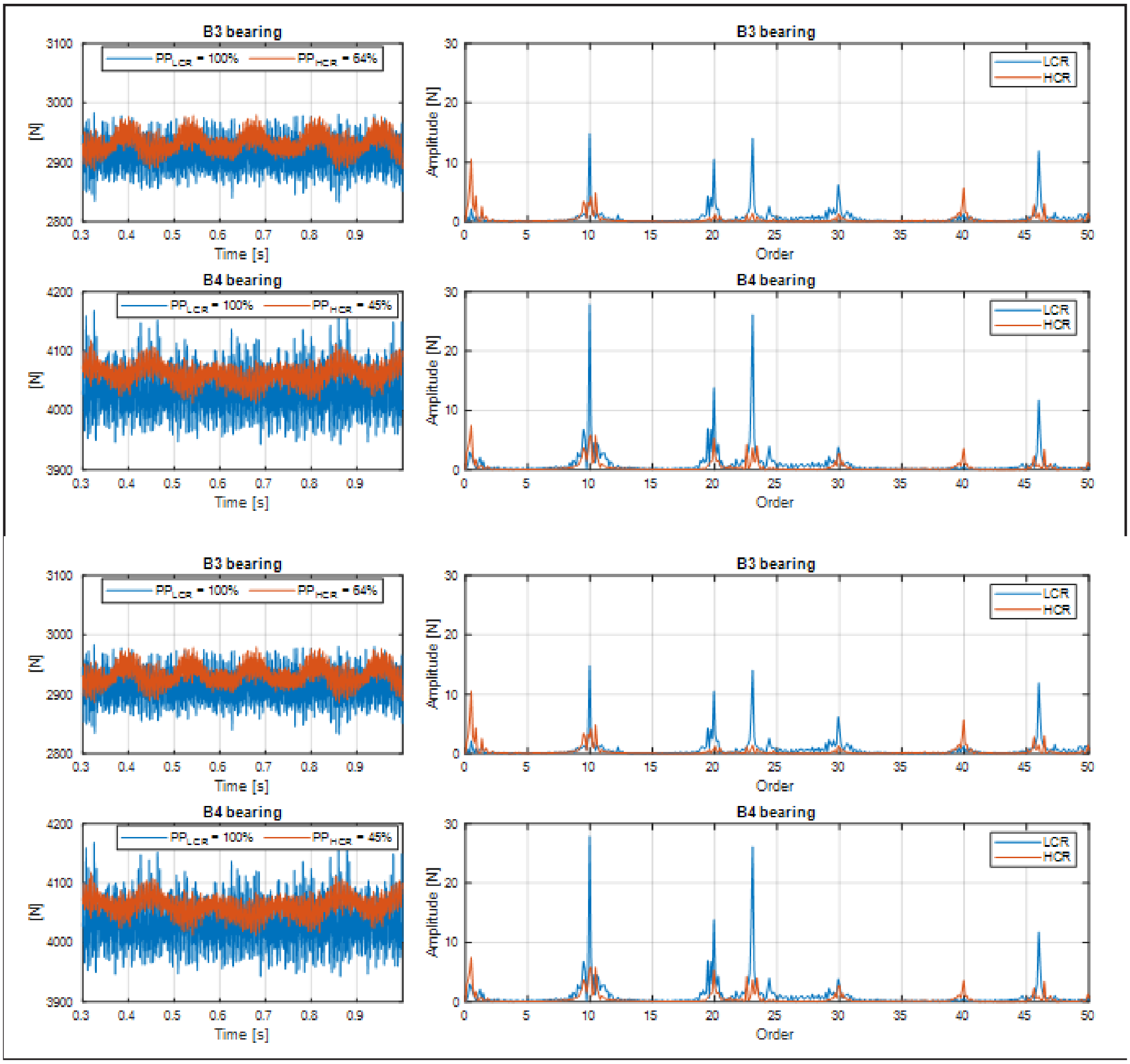

Figure 13 **Bearings forces FM – flexible housing. (con't)**

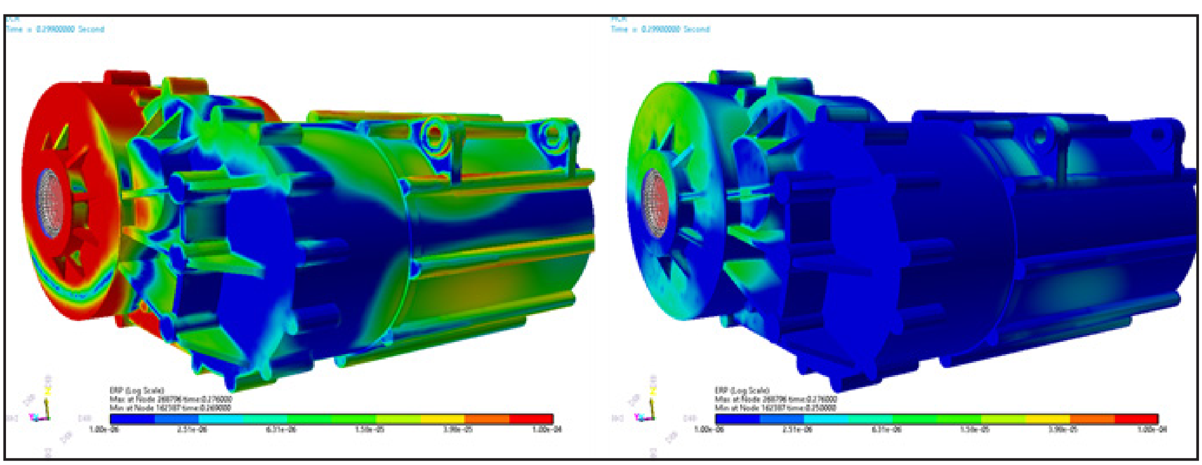

Figure 14 **ERP plot comparison: LCR (left) – HCR (right).**

Housing acoustic ERP. Acoustic equivalent radiated power (ERP) is defined as:

$$e_{ERP}=f_{RLF}\cdot ½\cdot C\cdot \rho\cdot \Sigma(A_i\cdot v_i^2) \quad (27)$$

where f_{RLF} is the radiation loss factor, C is sound velocity, ρ is the density of a target material that transfers the vibration (i.e. — the noise) as, for example air, A_i is the area on the *i-th* flexible panel and v_i is the face normal velocity on the *i-th* flexible panel; further details can be found in (Ref. 36).

In Figure 14 the comparison among LCR gearset and HCR gearset is presented in terms of equivalent radiated power: the brighter regions are representative of a higher sound power radiation, confirming the effectiveness of adopting HCR gears for NVH improvement.

The contour plot is very helpful to understand which is the contribution of each housing panel to the overall noise emission, and to address subsequent design modifications (local stiffening of the housing, e.g. — by means of ribs).

Conclusions

A methodology to analyze NVH performances of an automotive e-axle was addressed in the present paper. The proposed EV transmission was then designed using *KISSsys* and considering the gear microgeometry.

An extended Campbell diagram including the electrical and mechanical orders, together with the Eigenfrequencies of the constrained system, was calculated. Furthermore, the electric was modeled as a fully flexible multi-body system, and the forced response was calculated at the constant speed of the electric motor.

The NVH performance of high-contact ratio gears (HCR) was then evaluated with respect to standard ISO-53 gear profile A. Peak-to-peak transmission error (PPTE), gear meshing, and bearing forces have been compared for both configurations, showing the improvement of the HCR gears compared to the LCR gears on the NVH performance of the e-axle.

Finally, housing equivalent-radiated powers (ERP), resulting from both ISO-53 profile A and HCR gears simulations, have been compared showing the reduction of surface normal velocities. The critical areas for the design of the housing have been shown by means of contour plots.

Design improvements of the housing to minimize equivalent radiated power will be the object of further analysis.

For more information.

Questions or comments regarding this paper?
Contact Davide Marano at *marano@gear-lab.it.*

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Timo Giese holds a degree in mechanical engineering at Technical University Munich (TUM). He is currently Technical Director at Function Bay Munich. Giese's research interests are focused on NVH simulation of gearboxes, dynamic simulation of machine tools and simulation of tracked vehicles.


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Klingelnberg

NOMINATED FOR GERMAN INNOVATION AWARD 2021

Klingelnberg has been nominated for the German Innovation Award 2021 with its "Done-in-One — Complete Measurement in a Single Stage" solution. The German Innovation Awards honor products and solutions that distinguish themselves from earlier solutions primarily by their user centricity and added value. The German Innovation Award are granted by the German Design Council, which was enacted into law by the German Parliament in 1953 and is funded by the Federation of German Industries (BDI).

With its "Done-in-One — Complete Measurement in a Single Stage" solution, Klingelnberg will enter the "Machine and Engineering" category in the "Excellence in Business to Business" competition class. The company's approach is to perform various measurement processes in a single stage as one complete measurement ("Done-in-One"), all in the immediate production environment. A Klingelnberg Precision Measuring Center (G variant) has rapid measurement capability for dimensions, shape, contour and surface roughness in one automated cycle. By combining measurement tasks traditionally performed on up to four different devices, it is possible not only to lower investment costs, but also to decrease setup times and reduce quality costs. The integration of measuring technology into the immediate production environment, in particular, helps to increase the productivity and output of the production plants.

"We are honored to have secured a nomination for the German Innovation Award 2021 with the same award-winning solution that earned us the Best of Industry Award from *MM Maschinenmarkt* in June 2020," remarked Martin Boelter, CTO, Klingelnberg Group. "The nomination is a testament to our strong capacity for innovation. It is also evidence of our recognition in the market," said Boelter.

The jury is made up of independent interdisciplinary experts from industry, science, institutions, and finance. The submissions are judged on the criteria of innovation, benefit to users, and economic efficiency. The winners will be announced in February 2021.

www.klingelnberg.com

Tyrolit

ACQUIRES BIBIELLE S.P.A.

As a leading provider of grinding and dressing tools Tyrolit already offered a comprehensive portfolio of grinding solutions for many industries. Now, with the integration of the highly specialized Bibielle assortment, Tyrolit is able to meet all grinding, polishing, finishing and surface conditioning needs, down to the most niche customer requirements.

The basic raw material fiber is produced in-house and is used in countless non-woven (fleece) applications as well as in surface conditioning materials. This keeps the supply chain compact and short and also makes for great strategic growth potential outside of traditional target industries.

A wide range of products for finishing, masking and satin finishing combined with high tear resistance provides customers with the means for the best finish wherever a perfect surface is required. This includes, but is not limited to, design objects, surgical instruments, aircraft engines and turbine components, vanes, metal parts for boats, tanks and processing tools for chemicals and food, cutlery and jewelry.

Last year the Tyrolit Power assortment was further extended with the D105 REMOVAL strips. The D105 REMOVAL strips consist of electroplated diamonds on a polyethylene backing stabilized by natural brushes. With these new rougher strips it is possible to remove more material faster and still follow the surface.

The smooth transition of Bibielle S.p.A into the Tyrolit Group ensures that no know-how is lost and resources and insights are pooled, to create an even stronger market position. Both Tyrolit and Bibielle customers will profit from the acquisition through the creation of a one-stop shop and a widened sales network.

Experts are working closely together to realize the huge potential for growth by making use of many synergies, especially in the area of research and development.

www.tyrolit.com

Solar Atmospheres

ACHIEVES NADCAP ACCREDITATION FOR LABORATORY

Solar Atmospheres of Western PA (SAWPA) successfully achieves Nadcap AC7101/4 accreditation for their captive metallography laboratory and becomes an approved Boeing Process Source (D1-4426). The accreditation will allow SAWPA to test for microhardness, surface contamination, intergranular oxidation and grain size in accordance with various aerospace specifications including many Boeing process specifications. Furthermore, the accreditation will reduce Solar's dependence on outside testing facilities and provide its customers with a single source supplier capable of meeting all testing needs internally. Along with the laboratory accreditation, SAWPA continued the 24-month merit status for Nadcap heat treating.

Plant Metallurgist Greg Scheuring states, "This is a critical step for Solar Atmospheres of Western PA. We were missing out on a significant amount of production work and R&D projects because we were not qualified to certify test results to aerospace standards. Customers require a facility that can provide a one-stop shop." Scheuring continues, "But this is really just the first phase of a broader goal. With Nadcap accreditation, SAWPA can seek out approval from specific Primes like Boeing, who consider Nadcap accreditation as a pre-requisite for their own internal qualification procedures. This accreditation will open up many new opportunities for SAWPA moving forward."

www.solaratm.com

Bodycote

OPENS NEW ILLINOIS HEAT TREATMENT FACILITY

Bodycote recently announced the opening of a new facility in Elgin, Illinois.

The Elgin facility upgrades the company's capabilities and positions Bodycote as part of an ongoing strategy to provide the best possible capabilities and geographical network to better serve customers from the agricultural, mining, construction, automotive and various other manufacturing supply chains in the Upper Midwest region.

The brand new facility is now fully operational and supporting customer requirements. Bodycote continues to provide all of the processes and capabilities which were previously offered at the Melrose Park location. Additionally, the new state of the art facility in Elgin offers nitriding, Corr-I-Dur, nitrocarburizing and low pressure carburizing (LPC) solutions.

Stephen Harris, Bodycote Group chief executive, commented, "We're very pleased to announce the opening of the new facility in Elgin, Illinois. The purpose-built facility demonstrates Bodycote's commitment to serving the Midwest and helps us to shape the future of both our company and the industry."

Bodycote has more than 70 facilities in North America. There will be an official opening event when COVID-19 related restrictions are lifted.

Announces Further Expansion in North America

Bodycote is pleased to announce the opening of a new facility in Syracuse, New York.

The new Syracuse facility is the second new facility to be opened in North America in as many months, following on from the announcement of the opening of the new Elgin, Illinois facility in December 2020.

The Syracuse facility, encompassing 60,000 square feet of operating space, is now operational and offers a wide range of heat treatment processes. These include vacuum heat treating, atmospheric carburizing, low-pressure carburizing, carbonitriding, ferritic nitro carburizing, nitriding and aluminum heat treating. It is envisaged that the site will secure all major OEM approvals as well as Nadcap accreditation which it is already well on the way to achieving.

Stephen Harris, Bodycote Group chief executive, commented, "We are very pleased to announce the opening of another new facility in the USA, this time in Syracuse, New York. This investment demonstrates Bodycote's continuing commitment to align resources to serve our customers across North America."

There will be an official opening event when conditions allow.

www.bodycote.com

Universal Robots

REACHES 50,000 COLLABORATIVE ROBOTS SOLD

Collaborative robots — or cobots — remain the fastest growing segment of industrial automation, projected to grow at a Compound Annual Growth Rate (CAGR) of 30.37% during 2020–2025. Cobot market pioneer Universal Robots (UR) solidified its frontrunner position today by selling the 50,000th UR cobot, which was purchased by a German manufacturer to enable higher productivity and better employee safety.

The 50,000th cobot came in a special delivery as Jürgen von Hollen, president of Universal Robots, personally handed over the cobot to VEMA technische Kunststoffteile GmbH and VEMA Werkzeug- und Formenbau GmbH located in Krauchenwies-Göggingen, Germany, at a ceremony held at VEMA.

"We have worked very hard in the past 15 years to develop an entirely new market segment with a mission to enable especially small- and medium sized companies to automate tasks they thought were too costly or complex," says von Hollen, emphasizing how UR has created a new global distribution network, a new ecosystem of developers, and ultimately a completely new business model. "As a pioneer in this market, we put a lot of work into creating awareness, influencing standards, and changing customers' perceptions influenced by their experience of traditional robots."

Von Hollen noted that VEMA GmbH is a great example of UR's mission realized: "VEMA was looking for a cost-effective, flexible, easy-to-use automation solution they could implement, program and manage on their own. They found exactly that in the UR cobot."

Cobots enhance both productivity and quality

VEMA's new collaborative robot will join a fleet of three other UR cobots already deployed in pick and place tasks in end-of-line applications at the company.

Christian Veser, managing director at VEMA GmbH, is thrilled to be the recipient of the milestone cobot and explains how the cobots have enabled the company to add a third shift, now operating around the clock. "We have enhanced our productivity remarkably and also achieved better quality," he says. "Our employees are freed from ergonomically straining work to focus on quality testing. In navigating COVID-19 challenges, it has also been a great advantage that the cobots don't need to keep a safety distance or undergo quarantine. They can always work," says Veser, adding that his company appreciates the cobots so much that they gave them names.

"The first three cobots are named Elfriede, Günther and Bruno. We will name our new cobot Jürgen to honor the fact that UR's president came here in person to deliver it."

Jürgen von Hollen will be leaving UR at the end of the year after a four-year tenure at the helm of UR. "It is such a privilege to end my time at the company by marking this milestone," he says. "We have come far, but there is still an immense potential in the market both for well-known and completey new cobot applications. With our unrivaled installed base, we are constantly learning from our customers, leveraging a very data-driven approach in the development of our cobots. This is an approach I believe will help keep us leading the field in the years to come."

Gregory Smith, president of Teradyne's Industrial Automation Group, will step in to fill the role of UR president on January 1, 2021 until a new leader is named. "I thank Jürgen for his leadership over the past four years in growing Universal Robots from start-up status into the undisputed global leader in industrial collaborative robots," says Mark Jagiela, president and CEO of UR's parent company Teradyne. "He leaves behind a strong platform for the next level of growth with a talented workforce, an engaged ecosystem of distribution and technology partners as well as an expansive worldwide customer base."

www.universal-robots.com

VELO3D

PARTNERS WITH GOENGINEER FOR SAPPHIRE 3D PRINTING SYSTEMS

As demand for their industry-leading additive manufacturing systems grows, VELO3D has announced the formation of a U.S.-wide partnership with GoEngineer. GoEngineer will operate as an extension of VELO3D, dedicating resources to educate designers about the game changing potential of SupportFree technology for their designs, as well as sales and service expertise supporting the complete solutions portfolio including Flow pre-print software, Sapphire metal AM printer, and Assure quality assurance and control system.

GoEngineer will be VELO3D's largest partner in the United States; existing sales networks and direct purchase opportunities from VELO3D remain in place. With more than 35 years of experience and thousands of customers in high tech, medical, machine design, energy, and other industries, GoEngineer provides best-in-class design solutions including CAD, PLM, and 3D printers. The company has been the #1 global leader in sales of Stratasys polymer printers and the #1 North American leader for SOLIDWORKS for many consecutive years.

"We are pleased to partner with VELO3D to help manufacturing companies across the U.S. produce mission-critical parts for industrial use," states Ken Clayton, CEO of GoEngineer. "VELO3D delivers breakthrough SupportFree technology for the design and manufacturing of metal parts that are not hindered by geometric constraints nor compromised by part quality. Metal additive manufacturing is an important piece to GoEngineer's portfolio and we are excited to help our customers differentiate themselves even more."

"GoEngineer has gained the trust of thousands of customers with their rich expertise in additive design solutions. I see them as a strategic and invaluable partner in educating customers about the opportunity our technology brings to design and manufacturing. GoEngineer is a highly compatible national partner for VELO3D," states Benny Buller, founder and CEO of VELO3D. "Together, we will help end-users build what they want without the constraints of yesterday's standards. Design freedom, agile production, and quality assurance are requirements that VELO3D is uniquely positioned to meet."

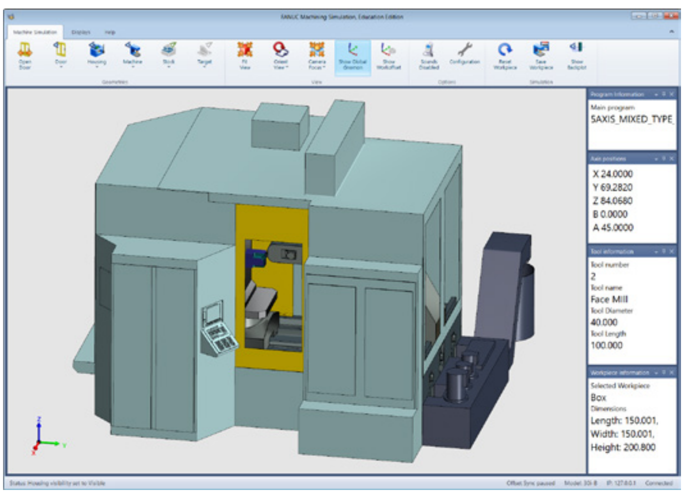
VELO3D is well-known for enabling geometric freedom through its patented SupportFree process, which reduces the consideration of support structures for complex passageways, shallow overhangs, and low angles. Coupled with their non-contact recoater, VELO3D's printing process can create the intricate cooling passageways and fuel delivery channels needed to achieve high-output fluid transmission and electrical power.

www.velo3d.com

FANUC

NAMED TOP WORKPLACE IN 2020

FANUC was recently named a top work place in Michigan by the Detroit Free Press for the ninth consecutive year. FANUC ranks 15 out of 30 companies in the large employer category in Michigan. In addition, the Chicago Tribune named FANUC's Hoffman Estate, IL regional office a top work place in Illinois for the third year in a row.



"I'm so honored that even during these challenging and unprecedented times of a global pandemic we've been named a top work place," said Mike Cicco, president and CEO, FANUC America. "This recognition is based on our employees' feedback, and I'm proud they feel that FANUC is an ideal place to work."

"Our team of talented professionals is our greatest asset — integral to our company's mission and key to FANUC's competitive advantage," added Cicco.

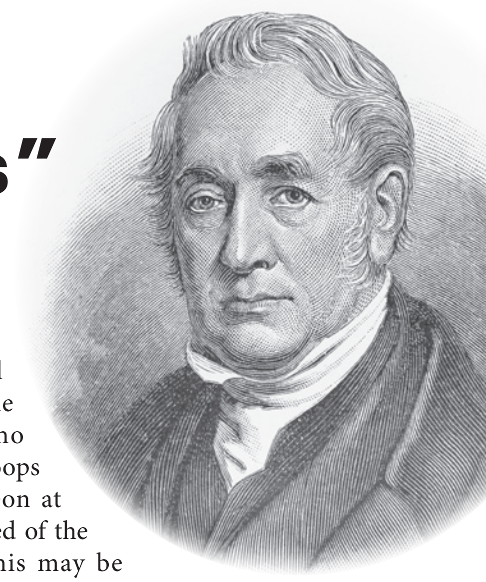
FANUC America's Achievements in 2020 include a number of new CNC and robotics products, a new facility in Alabama, national recognition for helping close the manufacturing skills gap, and a first-ever virtual event. These accomplishments include:

- The new 30i-B Plus Series CNCs incorporate enhancements to progress high-speed and high-quality manufacturing, such as a state-of-the-art CPU, for faster and increased processing power, and include features designed to simplify 5-axis machining.
- To further develop the next-gen manufacturing workforce, FANUC America expanded its CNC training offerings to include 5-axis CNC simulation. The machining simulation for workforce development provides virtual training for controls operation and part programming.
- The Quick and Simple Startup of Robotization (QSSR) G-code feature allows FANUC CNCs to control machine tending robots that provide assistance to machine tools. This benefits those shops that are unfamiliar with robotic programming language since the robots can now be programmed using ISO standard G-code.
- A new CRX line of collaborative robots offer a variety of unique attributes that set industry standards in terms of ease of use, safety and reliability. The CRX is easy to program and teach points using Manual Guide teach programming and a new tablet interface with icon based drag-and-drop program control — no programming knowledge required.
- A major expansion to its line of high-performance SCARA robots including the SR-12iA and SR-20iA with 12 and 20 kg payloads respectively. The added robot model variations offer companies versatile and high-speed options for a variety of applications including robotic assembly, robotic dispensing, robotic pick and place, and more. These two new SCARA robot models add to FANUC's already industry-leading range of industrial robots.
- A growing customer base prompted FANUC to open a new regional office in Bessemer, AL to provide automation for aerospace, automotive OEMs, their tier suppliers, consumer products, and a wide range of other industries.
- The U.S. Department of Labor recognized FANUC America, Rockwell Automation and other industry partners for apprenticeship programs designed to help companies overcome the skills gap. FANUC's education network includes more than 1,200 high school and post-secondary FANUC-certified automation training organizations, and over 150 university and career technical training partners, providing students with nationally recognized FANUC robotics certification and CNC certification.
- FANUC held its first virtual event called "Take Control". Launched on Oct. 19–22, the event site includes three distinct zones: Knowledge, Solutions and Exploration. FANUC invites those looking to solve manufacturing problems to visit and learn how automation is helping companies achieve their goals.

www.fanucamerica.com

George Stephenson, "The Father of Railways"

Jack McGuinn, Senior Editor

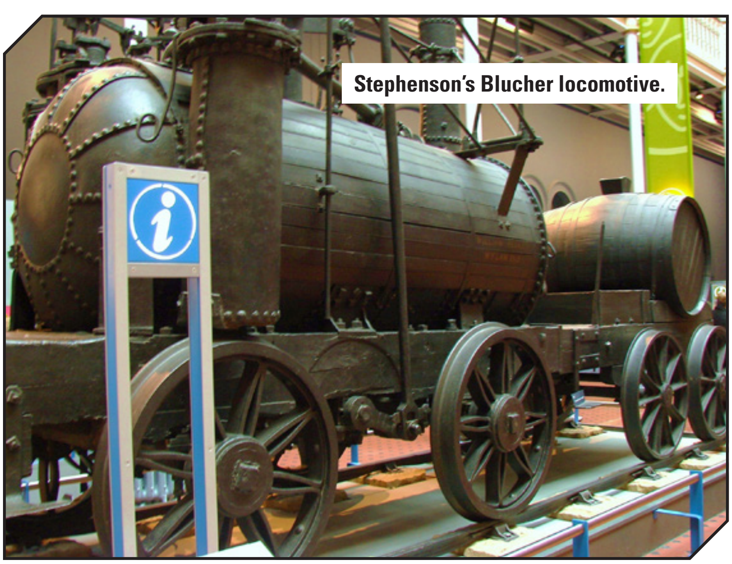


While high-speed rail development continues around the world, let's take a minute to consider the achievements of George Stephenson (1781–1848) — "the father of railways" and inventor of the first commercial locomotive and other significant achievements.

Born in England in 1781 near Newcastle, to illiterate parents and the son of a coal miner, there was no money available for formal schooling. So Stephenson did farm work, including cowherding. Soon, at age 10, he's driving the horses that carry the coal carriages on the tramway going past his family's one room cottage. Everything in the area revolves around the local pit and the rapidly expanding coal industry. One of George's next jobs is picking stones out of the coal.

He then went on to working on the mining machines that lift miners up and down into the mine. After finding work as an engine man, at 17, Stephenson paid for his own night school education. At 18, he can now read, write and do arithmetic. Married at age 19, the couple lives in a one room cottage, and a year later, his first son is born. For extra income George does cobbling and repairs clocks along with his regular job. Sadly they have a daughter, who at three weeks old dies, followed just months later by Stephenson's wife.

Now looking for work, Stephenson is forced to leave his son and go to Scotland, but he returns to care for his father when he's blinded in a mining accident. When Stephenson figures out how to repair a broken pumping engine, he's put in charge of all the mine equipment. He then proceeds to breaking down and reassembling machines and engines whenever possible, and develops an intricate understanding of steam-driven machinery. In 1814, Stephenson combines the tramways and the steam engines to make the first commercially viable locomotive. 'Blucher' is built to haul coal and is named after the Prussian General who speed-marched his troops to help defeat Napoleon at Waterloo. The top speed of the Blucher is 4 mph. This may be slower than a horse can travel but the trains' eight wagons carry far more coal, thus hastening the end of horsepower.



Stephenson's Blucher locomotive.

But the Blucher is prone to repeatedly breaking down, and its power and weight chew up the tracks. However each breakdown spurs Stephenson onto another solution. In 1819 he creates an eight mile railway in Sunderland — *the first railway to be solely machined powered*. He patents his own cast iron rails and two years later he's appointed engineer for the construction of the Stockton and Darlington railway. When Stephenson finds another man has invented better rails, he acknowledges that sometimes the best idea is somebody else's; he scraps his own invention and despite the cost uses the improved version. Stephenson, now remarried, opens his railway in 1825. It's the first public railway in the world. The first locomotive on it is the aptly named "Locomotion." The company, set up with his son Robert, is the first in the world to build locomotives.

Significantly, Stephenson sets the width (or gauge in trainspeak) between the rails at four feet eight and a half inches. Stephenson's measurement will become the standard width first throughout Britain, and then the world.

Stephenson and Brunel would clash many times over their different visions for rail as their Northern and Western Lines come perilously close to each other. In 1829, railway owners staged a competition to find the best locomotive. Mindful of destroying the rails, only machines under six tons could compete. Ten locomotives apply. Five fail to make race day. Two further fail because of mechanical problems. Thousands of spectators witness Stephenson's 'Rocket' achieve a record 36 mph and take the prize. With that, Americans flock to him, desperate to take his trains and techniques back with them to the U.S.

In 1830, the Prime Minister and hero of Waterloo, the Duke of Wellington, is just one of the VIPs to attend the opening of the Liverpool and Manchester railway in 1830. Stephenson now receives more work and more money than he can handle. Excavations for his railways discover coalfields that make him rich enough to buy land and a large house. He tours England talking about how rail took him from rags to riches.

On August 12, 1848, Stephenson died in Chesterfield, Derbyshire. The inventions he leaves behind accelerate the industrial revolution and help make the modern world.