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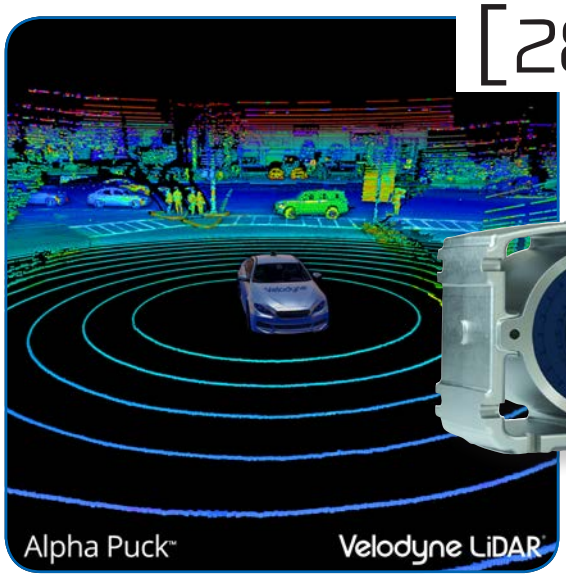

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FEATURE ARTICLES

TECHNICAL ARTICLES

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Power Transmission Engineering
VOL. 13, NO. 2

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Keeping the world in motion >>

Randy Stott, Managing Editor

Manufacturing Economy 2019: A Summary

By most measures, and according to most observers, the manufacturing economy continues to hum along. U.S. manufacturing has been in growth mode for several years, although the rate of growth has slowed, and most are predicting that it will continue to slow throughout 2019.

- The February report of the Institute for Supply Management put the PMI (purchasing managers index) at 54.2%, indicating expansion in the manufacturing economy for the 30th consecutive month (compared with 118 consecutive months of expansion for the overall economy). However, this was the lowest PMI reading over the last 12 months. (*www.instituteforsupplymanagement.org*)
- The Power Transmission Distributors Association's announced that its PTDA Business Index (modeled after the ISM's PMI) registered 57.9 at the end of 2018. This was a downward shift from the third quarter reading of 63.1. The association is also predicting growth in 2019, but at a slower pace (*www.ptda.org*).
- NEMA's Electroindustry Business Conditions Index (which also follows a similar model to ISM's PMI) has seen a significant uptick in recent months, with the January 2019 result at 53.3 and the February 2019 result at 55.9, after several sub-50 readings at the end of 2018 (*www.nema.org*).
- The U.S. Federal Reserve reports that industrial production decreased 0.6 percent in January. Manufacturing production (excluding mining and utilities) decreased 0.9 percent in January. Mostly, this was due to a decrease in automotive production (*www.federalreserve.gov*).

Meanwhile, we're all still trying to figure out the long-term effects of the ongoing trade war. Tariffs on steel and aluminum are helping some, but hurting others. Last year, Ford CEO James Hackett claimed the tariffs would cost the automaker $1 billion in profits, and Harley-Davidson announced it was moving some production to Thailand to offset increased costs related to the trade war. Retaliatory tariffs are making life difficult for U.S. farmers and food producers.

This is all complicated by the fact that we still face an extreme skilled labor shortage. Most of you could probably expand your business if you had the people in place to take advantage of the opportunities in front of you. But those people are hard to come by.

Everyone knows that the economy runs in cycles. Eventually, the current economic expansion is going to end. A contraction is coming. The only question is when.

So a lot of companies are taking a very cautious, wait-and-see approach. They're holding off on investments, hedging their bets in case the downturn comes sooner than expected.

I watch, read and listen to a lot of prognosticators. Most think 2019 is going to remain okay for the manufacturing economy. There will still be growth, but it's going to continue slowing down, especially in the second half of the year. Nobody knows when the expansion will end. I certainly don't.

But what I do know is that it's never a good idea to hold off on investments that can improve your business. Every issue we bring you examples of how power transmission components are becoming smarter, more efficient and more capable. If you have the opportunity to upgrade your equipment, take advantage of Industry 4.0 and give your employees the chance to transform your business, you shouldn't wait around for someone to tell you the time is right. Nor should you hesitate to train your employees, hire people with new skills or find ways to bring more talent into your organization.

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Liebherr Components

OFFERS DIVERSE PRODUCT PORTFOLIO AT BAUMA 2018

Liebherr Components is presenting a new line of slewing bearings at this year's Bauma. Particular focus lies thereby on maximum torque and ease of service.

Liebherr is further expanding its existing slewing bearing portfolio with new slewing drive units. The new product line includes worm gear drives, pinion drives and toothed belt drives.

Liebherr's worm gear drives are ultra-compact slewing drive units with high power density. This design is particularly suitable for the transmission of extremely high forces and torques in small spaces. These worm gear drives find use in steering gearboxes of crane and heavy-duty vehicle chassis, loading cranes or agricultural equipment. Liebherr continues to develop the product specifically for these applications with the goal of maximizing torque and minimizing maintenance costs.

Slewing drive units are driven by a hydraulic or electric motor. Worm gear drives combine slewing bearings with a drive worm. The worm gearing transmits the torque to the slewing bearing without clearance. Liebherr offers a running tread diameter of up to 725 millimeters. The slewing drive units are available with single-start or doublestart, double-bearing worms, which allow for self-locking of the drive depending on the efficiency. A brake option can be adapted for all other versions. Grease or oil can be used for lubrication.

The pinion drives are generally driven via a double supported pinion. This type of slewing drive unit is characterized by a fast rotation speed with low heat development. This design is a perfect combination of Liebherr's own slewing bearings and drives.

The toothed belt drive is ideal for high circumferential speeds, high efficiency and particularly quiet operation.

The use of special material allows the component to be used in the machine environment at very low temperatures.

This new Liebherr product line further expands the range of products offered by Liebherr Components. This is possible due to the vast experience in the production of components in the area of slewing bearings and drive technology. Liebherr's innovative team is constantly working to develop and produce slewing drive units in order to meet the needs of our customers with new products.

Liebherr is also optimizing its existing product portfolio of planetary gearboxes with the LPI gearbox generation. The new series includes seven basic gearboxes from LPI 600 to LPI 1200, covering a torque range from 20,000 Nm to 335,000 Nm. Large tailor-designed gearboxes with a dynamic torque of up to 2,300,000 Nm can also be produced.

The significantly reduced complexity and standardization of the components make the gearboxes easier to configure for any application. It is predestined for lifting applications, for example in rope winches, as well as for driving applications, for example as drives for chain and crawler vehicles.

Higher output torques with optimized weight and space LPI planetary gearboxes are designed for use in both stationary and mobile applications. They impress with their high power density and score points with their minimal weight and reduced installation space. The use of new manufacturing and material technologies has increased the permissible output torques by 20% compared to existing planetary gearboxes.

A wide range of configuration options ensures that the gearboxes are ideal for all common applications in which planetary gearboxes are used.

The planetary gearboxes of the new LPI series can be equipped with different brake sizes according to customer and application requirements. Depending on the intended use, various types, such as electromagnetic brakes or multidisc brakes, can be used.

The interfaces to the engine are even designed to allow for the effortless assembly of any commercially available electric and hydraulic motor. This ensures the best possible gearbox/ motor drive combination.

Depending on the application, the gearbox seals are designed as radial shaft seals, V-rings, mechanical seals or labyrinth seals. In the area of oil control and ventilation, the customer can choose between a large number of oil measuring devices and expansion vessels.

For more information:

Liebherr Components AG
Phone: +41 56 296-4300
www.liebherr.com/gearboxes

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Nord Gear

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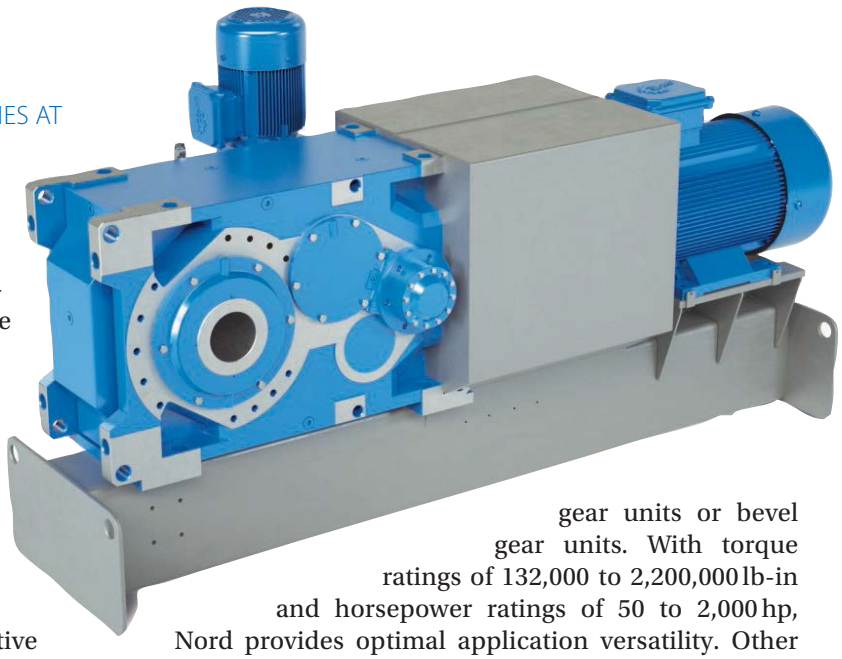


During the Grain Elevator and Processing Society (GEAPS) Exposition, March 9–12 at the Ernest N. Morial Convention Center in New Orleans, Nord Gear Corporation experts recently provided an exclusive look at new products, motors, conveyors and drive components for the grain industry.

Hani Almoghrabi, Nord's large industrial drives product manager, discussed the newly released MaxxDrive XT, which delivers a full package for bulk material handling. The optimized housing geometry allowing maximum thermal ratings among many other features and benefits were discussed by Almoghrabi during the show.

Additional product highlights included:

A Grain Endurance Package (GEP), a cost-effective bundle of product features designed specifically for grain processors. Included in the GEP is a Quadrilip sealing system, a keyless hollow shaft connection, safety cover, Donaldson T.R.A.P. breather, quick disconnects, and an oil sample port. Together the components assure long-lasting performance even in the harshest grain processing environments.

Nord's MaxxDrive series of industrial gear units, ideal for heavy duty applications, are available as parallel helical gear units or bevel gear units. With torque ratings of 132,000 to 2,200,000 lb-in and horsepower ratings of 50 to 2,000 hp, Nord provides optimal application versatility. Other benefits include a keyed and press-fit gear mounting system for maximum power transmission, leak-proof lubrication regardless of shaft orientation, a symmetrical housing design that provides for mirror image installations, various temperature management options, and a design that's been proven through extensive finite element analysis validation.

Nord's line of compact, helical bevel gear motors are available with cast iron or aluminum alloy Unicase housings, a

wide range of flange offerings, up to 250 hp and 440,000 lb-in of torque. They're ideal for mixers, conveyor belts, mills, and other demanding applications where long service life and flexible mounting.

Nord's Screw Conveyor Package offers a compact design that simplifies installation and maintenance of any conveyor. Its Quadrilip sealing system boasts primary and secondary Viton seals, a dust lip around the output shaft, and a grease-packed felt seal for additional protection against contaminants. As with any Nord drive unit, a number of mounting orientations are available (six, in this case, as well as the option to tilt the unit at an angle), and its modular design provides tremendous flexibility in the field. This means fewer parts, greater efficiency, lower costs, and less hassle.

For more information:
Nord Gear Corporation
Phone: (888) 314-6673
www.nord.com

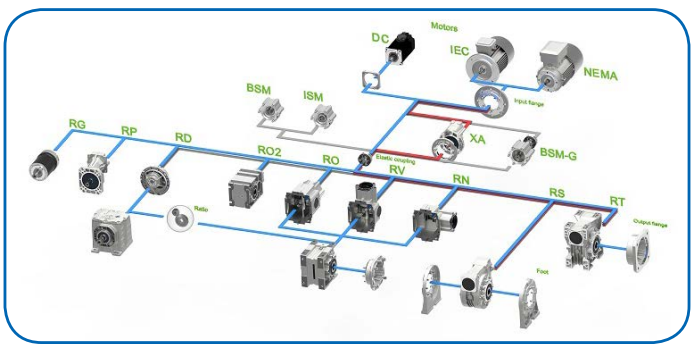
Varvel Group

FOCUSES ON HIGH MODULAR GEARBOXES

The need to keep customers in all parts of the world constantly supplied while minimizing stock in distributors' warehouses, and a range of gearboxes offering many thousands of possible configurations were the two elements that encouraged Varvel to develop the concept of modularity and design end products that could be configured in just a few simple steps using kits. Today, modular design is a key strength and has made Varvel a model for advanced Italian engineering.

Varvel is present in over 60 countries around the world. In 2000, the company decided to extend the concept of modularity already applied to its worm gearboxes to its entire product range. Varvel's parallel shaft and bevel-helical gearbox and gearmotor ranges were the result of this decision.

Today, Varvel's entire product range, which extends up to 3,400 Nm of transmissible output torque and 22 kW of installable power, is designed and made using modular kits to create thousands of different configurations. Every parallel shaft and bevel-helical gearbox is made up of an input kit (motor flange and coupling), an intermediate kit (gear pair) and an output kit (casing, output shaft and gear train) to which accessory kits (like torque arms, feet, flanges etc.) can be



added. Within each size, kits can easily be selected to create different gearbox types (parallel shaft or bevel-helical), different reduction ratios and an impressive choice of outputs (shafts) and inputs (motor sizes).

The main beneficiaries of such high modularity is Varvel's distribution network of over 100 commercial partners around the world. Varvel's modular kits have led to a dramatic reduction in stock and lower costs for distributors and dealers while permitting an excellent level of service. This win-win solution has proved a tremendous advantage not just for Varvel but for all stakeholders.

Modularity has brought with it an economic and competitive advantage that is achieving excellent results even in the United States, where Varvel opened a subsidiary in 2017. The U.S. market has responded to the Varvel formula in an extremely positive manner and Varvel's high modularity is proving a distinctive feature with respect to the local competition.

With digital solutions becoming more important every day, Varvel has introduced *VARsize* to support its "mechanical modularity." *VARsize* software allows users to select exactly the right size for their needs and even provides 3D models instantly. All Varvel products can now be configured and assembled quickly and easily anywhere in the world.

Varvel's emphasis on modularity is not just a matter of strategic marketing but also a major enhancement for distributors and dealers, who can add value to their local services and play a far larger role without incurring excessive costs. In business, everybody has to perform to the best of their ability in pursuit of a common objective. In this context, modularity represents a valid systemic model and a way to optimize the supply chain to the advantage of all concerned.

For more information:
Varvel Group
Phone: (770) 217-4567
www.varvel.com

Bonfiglioli

OFFERS SLEW DRIVE SOLUTIONS FOR AUSTRALIAN PORT FACILITY

With the increased trade with Asia and the growing Australian economy, port facilities have greatly expanded in recent years. Stacker reclaimers are playing a key role in this, allowing stacking, blending and reclaiming of bulk material. This typical application involves long work hours in harsh environments and extremely heavy handling, so the choice of a resistant, efficient drive solution is critical.

Thanks to its local Customer Application Engineering team, Bonfiglioli Australia has helped its customer develop a customized solution that can boost the machine, consume less energy and provide ultimate reliability.

The two slews use three Bonfiglioli 316 planetary bevel

gearbox slew drives, with one spare always available to minimize downtime and production loss. Installed to power a stacker reclaimer for the stockpile area at a major Australian ship loading facility this solution delivers safety, durability and performance.

"Despite the engineering complexity and specifying nothing but top-quality parts from Australia and Italy, Bonfiglioli's drives were still more cost-effective than the older drives they were replacing," says Bonfiglioli Lead Project Engineer, Harry Singh.

The slew drives are vital to operational efficiency, and to ensure smooth operation at all times, Bonfiglioli's slew drives offer double backup for enhanced safety.

"In addition to the usual torque limiter found on most drives, these custom-engineered slew drives have a secondary encoder on the bevel stage. This has sensors to measure the drive at slow speeds and send data to the PLC [programmable logic controller], which will stop the drive if any problems are detected," says Singh.

To provide additional safety for hassle-free operation, these drives feature a secondary sensing device (proxy sensors) that can identify any marginal speed errors between the motor and gearbox shaft. The sensors and all component parts of the drive were sourced from globally proven and ISO-certified brands.

Thanks to its highly qualified local team and its global capacities, Bonfiglioli has supplied extremely customized slew drives to suit the customer's unique application requirements.

"When designing these drives, our Customer Application engineers built upon a safe, durable, reliable base – the 316 slew drive – and added additional safety and efficiency features to suit the customer's requirements," says Bonfiglioli Australia Country Manager, Malcolm Lewis.

All Bonfiglioli slew drives are easy to install and have precise torque control to ensure smooth, accurate performance in a wide range of applications.

For more information:
Bonfiglioli
Phone: (859) 334-3333
www.bonfiglioli.com

Mitsubishi Electric Automation

OFFERS HANDHELD MODELS FOR GOT2000 SERIES HMI

Making it easier than ever for machine operators and maintenance personnel to monitor and control machine components, Mitsubishi Electric Automation introduces handheld models for its GOT2000 Series, a human machine interface (HMI) that optimizes operator control and monitoring of device and line status. The GT25 Handy GOT, a portable interface offered in both 5.7-inch and 6.5-inch models, connects to industrial automation devices, including programmable logic controllers (PLC), variable frequency drives, servos and temperature controllers.

The handheld HMI displays information on a high resolution VGA touchscreen and allows operators to easily carry it with one hand. While its compact design allows operators to work wherever they can best observe physical machine changes, the GT25 Handy GOT provides powerful functionality.

"Freedom of movement allows users to take the HMI around the machine and make changes or monitor status from a convenient location, which is a huge benefit for maintenance personnel and machine operators in a variety of industries, especially automotive," stated Lee Cheung, product marketing engineer, Mitsubishi Electric Automation, Inc. "The GT25 Handy GOT is an external connection interface, so it can be easily connected or removed as needed."

The GT25 Handy GOT can be used in any application that involves local setup, operation, monitoring and maintenance of system components from a graphical interface in which mobility is required. It can also be used as a teach pendant for robots. Multiple safety and security measures, such as an emergency stop switch and an enable switch keep the operator safe in case of emergency.

For more information:
Mitsubishi Electric Automation, Inc.
Phone: (847) 478-2100
us.mitsubishielectric.com/fa/en

SDP/SI

INTRODUCES FLEXIBLE COUPLING EQUIPPED WITH VIBRATION DAMPING TECHNOLOGY

Stock Drive Products/Sterling Instrument (SDP/SI), a leader in providing mechanical based design, engineering, and precision manufacturing services for critical motion control and small power transmission applications has introduced several new series of high-gain couplings.

These Antivbration Flexible Couplings are designed for use with high gain servomotors. When a servomotor drives a mechanism, as in applications such as semiconductor manufacturing equipment, blood analyzers or high speed printers, a change in direction causes a phenomenon called hunting. Hunting is vibration in the system which reduces transit time making the equipment less efficient.

The Antivibration Flexible Coupling features a unique construction of vibration reducing rubber (FKM) molded with aluminum hubs. The resulting rubber lined finger-like structure allows for optimal torsional rigidity and damping. Three types are available in bore sizes 3 mm thru 16 mm, compact (S50GS2MA...), high-torque (S50GT2MA...), and long (S50GL2MA...). The sixty-one Antivibration Flexible Couplings are available as standard catalog items and can be easily purchased through the sales department or online at the SDP/SI E-Store. Detailed product specifications are available on the website.

SDP/SI offers a wide variety of mechanical component choices for the engineer, including a comprehensive selection of rigid and flexible couplings. Sr. Development Engineer, Mike Yandolino said, "The addition of this new precision flexible coupling line provides our customers with the very best solution for use in high speed and high precision servo systems."

Yandolino continued, "Providing position accuracy, vibration reduction, zero backlash, and quiet operation this coupling will become the preferred choice for many applications." The high torque capability of the coupling results in the ability to downsize the component used.

For more information:
SDP/SI
Phone: (516) 328-3300
www.sdp-si.com

Systematic Improvement

With AGVs, a primary bottleneck on productivity is battery life. But when looking at an AGV as a full system, there are plenty of ways this bottleneck can be widened.

Alex Cannella, Associate Editor

No matter what industry you work in, productivity will always be a concern. No matter how good a product or factory line's uptime might be, it can always be better — until the day everything runs entirely on automated machines 24/7, anyway. Which means that there will always be a perpetual mission to find whatever productivity bottleneck is most hampering production and chip away at it.

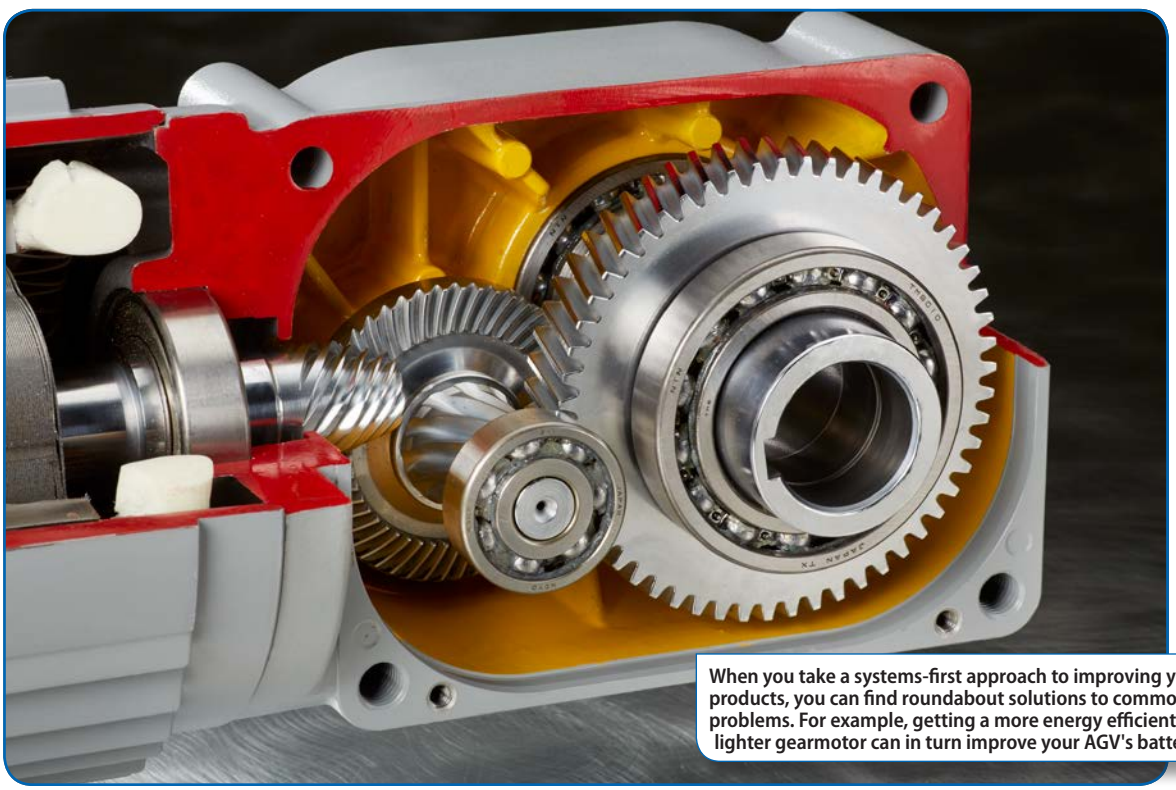
And for automated guided vehicles (AGVs), the primary productivity bottleneck of the day is battery life. Every trip back to the dock to recharge is lost productivity, and so the clear target is to reduce the amount of time spent charging, either by reducing how long it takes to charge or how many trips to the charging station need to be taken. And the obvious first step would be to just make a bigger, better battery, or a faster charging one — solutions that target the battery and directly affect our two limiting factors.

Or is it? There's a whole host of other, largely straightforward ways you can improve battery life if you just shift your approach a bit and look at the issue not as an isolated battery problem, but as a systems problem.

For example, take lightweighting. Basic physics declares that the heavier something is, the more energy it takes to make it move, so if you lighten the load, you'll require less energy to move the same distance. You already see this concept readily embraced in plenty of places, particularly automotive fields, but it also applies to AGVs and battery life. Since a battery's primary limitation is that it can only hold a limited amount of energy, it stands to reason that by lowering the vehicle's overall weight, it will draw less from the battery and the battery will last longer, improving productivity.

The benefits of lightweighting apply doubly for AGVs, as starting to move something draws more energy than keeping it in motion, and many automated machines, including AGVs, frequently start and stop. It becomes all the more important, then, to reduce the amount of power required to make the AGV move and consider weight when picking or making components.

That's all a pretty straightforward and simple concept when you think about it, but it's also a solution that requires you to look past the battery itself, consider the entire AGV as a system, and think about how components affect each other. A sort of forest versus trees solution. And it's just one of a number of potential ways you can improve your machine's battery life.



When you take a systems-first approach to improving your products, you can find roundabout solutions to common problems. For example, getting a more energy efficient or lighter gearmotor can in turn improve your AGV's battery life.

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Power density falls into a similar vein as lightweighting, but comes from a different angle. Any given application only needs so much torque to work, and at that point, you can compare components such as motors for their power density, essentially shopping around for the component that can do the same job with the smallest footprint.

Possibly the greatest systems-based change you can make, however, is to use more energy efficient components. It's the reverse concept of lightweighting. Energy efficiency is primarily a concern of energy conversion, of how much power is lost during the process of converting electricity to actual force. The more efficient a component is, the less energy is lost during that process, and the less overall electricity is drawn from the battery.

Again, nothing about either of these concepts is anything *new*, per se. They come up everywhere. Making increasingly compact motors is always a priority in a number of fields. Similarly, energy efficiency has been popping in and out of the news every time a new regulation milestone gets mandated, and companies that push the efficiency of their components even beyond those regulations are quick to point out the cost benefits over time of doing so. But it requires you to look outside the battery for solutions to a battery-based problem and take a systems-first approach to design, something that doesn't always happen from the start when developing new products.

It's also worth pointing out how all these different methods all synergize with each other. With a lighter AGV, you don't necessarily need as much torque to get it moving, and thus can use a smaller motor, which in turn leads to a lighter AGV, and both of the above can help improve a system's overall energy efficiency.

However, this still leaves us with a question: How exactly do you accomplish all those things? They may be simple solutions, but the actual steps to accomplish them are less so. It's not as if you can just walk outside and find more lightweight but equally durable components, or just decide you're going to make your motor 20% more efficient. These things take hard work and a dedicated engineering team to figure out, and even once you do, it's just back to the drawing board to see how you can do it again. So I sat down with the VP of Brother's Gearmotor Division, Matthew Roberson, to get a few examples of how component manufacturers are working to hit those goals.

"It's all about the systems," Roberson said. "So we're taking it from the systems approach, where if you're trying to get efficiency, you don't just look at the battery. You have to go through the components. And our components, we're on the drive train."

Roberson's primary answer for Brother was to move from using worm gearsets in their gearmotors to hypoid gearing, and the primary benefit here was in the field of energy efficiency. Brother's testing found that gearmotors with worm gear sets often only had an efficiency of 40–85%, depending on the gear ratio of the motor, compared to hypoid gearing's 95-99% efficiency. Depending on the application, that is a

significant gain. At a 10:1 ratio, a 10% improvement is still significant, but when you look at the other side of the scale where Brother tested, where a worm gearset with a 60:1 ratio only averaged 40% efficiency while a hypoid still managed 95, the difference is night and day.

According to Roberson, the primary reason for the massive leap in efficiency primarily was due to friction between the gears, or rather, how a hypoid set had significantly less of it. Worm gears undergo significantly more friction as the gears slide along each other compared to hypoids' meshing movement.

And this is where we come back to an earlier statement of mine. AGVs start and stop fairly often, which already antagonizes those differences in efficiency. But here again, Brother found the worm gear lost out even worse compared to hypoids due to the friction that had to be overcome to get the worm gears moving again. The result is that Brother found hypoid gears more efficient across the board and capable of handling higher initial inertia loads than a worm gear set, meaning better power density and thus less energy consumed every time that AGV starts moving.

That's not the end of the benefits Brother found, either. There's also the concern about where all that lost energy from less efficient gearing goes — aka the heat it produces and disperses to the rest of the system.

"Usually energy losses mean less amperage," Roberson said. "It's being transferred to heat instead versus transferred to power on the wheel...What that also means is that the gearmotor runs hotter. It's more challenging. It's more challenging for the seals, it's more challenging for the bearings, it's more challenging for the system."

Speaking of productivity killers, waiting for replacement components after something fails can be one of the worst, a constant bane of almost any machinery line. Finding a way to reduce wear and stave off eventual failure is pretty up there when it comes to convenient side perks.

Brother also offers some of the usual suite of value-added services that come with custom-built components such as "plug and play" designs. Continuing their systems-centric focus, there's an emphasis on designing components that fit inside the larger system of the product the components are being designed for. This also leads to other design decisions such as making their gearmotors grease-lubricated, which allows for the motors to be mounted in more configurations than their oil-lubricated counterparts.

When it comes to improving battery life, Brother's gearset swap is only one example of the overall process, but hopefully it illustrates how taking a full systems-wide approach to a project can open up more avenues to tackle it from compared to honing solely in on the primary component involved, and can help you better choose what to include in your AGVs once you adopt that approach.

For more information:

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In Motion

Latest product technologies focus on reducing costs and improving performance

Matthew Jaster, Senior Editor

The following special product news section examines the latest products and technologies in motion control. For additional information, be sure to check out motion control articles in the PTE Library at *www.powertransmission.com/subjects/motion%20control/*.

Single Phase Power Solutions

OFFERS 100 HP SINGLE-PHASE ELECTRIC MOTOR

Single Phase Power Solutions introduces a 100 hp single-phase electric motor. The Belle Single-Phase Motor uses Written-Pole technology to deliver a 100 hp single-phase motor that is compatible with readily-available single-phase utility services. The utility-friendly starting and operating characteristics provided through the use of Written-Pole technology minimize voltage sags and flicker on long single-phase distribution lines. Ideal for industrial applications in areas where three-phase power is not readily available or cost-effective, this revolutionary technology eliminates the need for phase converters or complex variable frequency drive installations.

Featuring a totally-enclosed fan-cooled design in a cast iron frame, this proven design is suitable for indoor or outdoor installation in some of the most demanding environments and applications. Rated as a 100 hp, 460 v, 1,800 rpm electric motor, this innovative design delivers 95.5% efficiency at rated load with a near-unity power factor. The NEMA 449T frame motor weighs about 2,700 pounds and draws just 170 amps at full load.

The motor windings are fabricated using high-grade copper and Class H insulation materials similar to those used in premium three-phase electric motors. The revolutionary design eliminates brushes, slip-rings and internal rotary switches, ensuring superior performance and reliability under harsh conditions.

Available in ratings from 30–100 hp, Belle Motors are ideal for many industrial, agricultural, mining, municipal, and oil& gas applications such as pumps, compressors, injection wells, as well as blowers, fans, dryers, water & wastewater processing and more.

For more information:
Single Phase Power Solutions
Phone: (877) 430-5634
www.sppowersolutions.com

Thomson Industries

INTRODUCE BALL SCREWS FOR MAXIMUM LOAD CAPACITY

Thomson Industries, Inc. has introduced a ball screw with more than twice the load capacity of a standard ball screw. The redesigned ball screws handle more than double the load capacity or provide 10 times the service life compared to standard ball screws at equivalent performance points – along with Thomson's characteristic German-engineered precision, high reliability and exemplary stiffness. High-load ball screws are ideal for demanding motion control applications such as injection molding, pressing and large fabrication equipment.

"By increasing ball size and optimizing ball track design, we now offer a ball screw that handles more than twice the capacity of a comparable standard ball screw. And because roller screws have a nut that is close to 50% larger at 150% the price of a comparable high-load ball screw, motion control system

designers now have an attractive opportunity to reduce costs while improving performance," said Thomson Product Line Specialist EMEA & Asia for Screws, Markus Brändle.

Thomson high-load ball screws minimize replacement and maintenance costs significantly for the application. This provides an ideal opportunity to replace roller screws or hydraulic systems in applications with axes that require accurate and safe movement of heavy loads, long and reliable life, and minimum maintenance. These applications include large fabrication equipment, injection molding, metal fabrication machines, metal pressing/forming applications and a wide variety of other demanding applications.

Thomson high-load ball screws are available with up to 15 m screw lengths and with single or double nuts. They come in standard sizes up to 160 mm in diameter with up to 1,440 kN of dynamic load capacity. Preloading options are available upon request, and Thomson will customize the ball screw to meet customer-specific applications. They provide smooth, quiet motion at higher speeds over a longer life. Lead accuracy is up to 12 µm/300 mm.

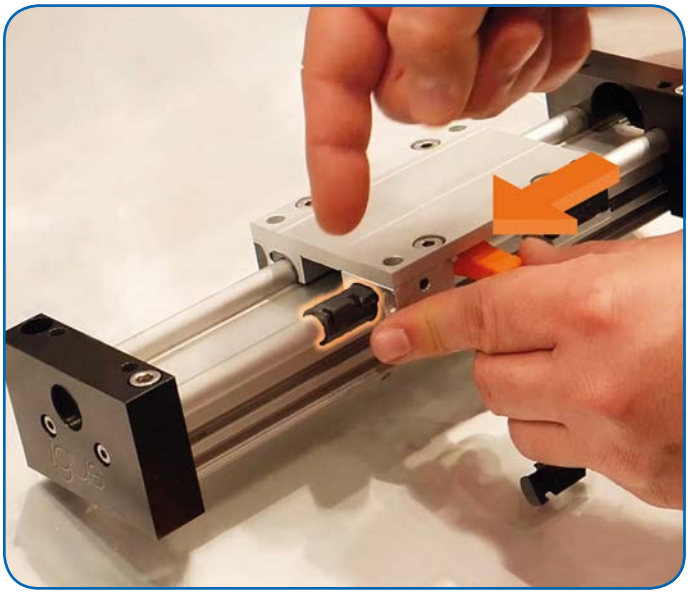
For more information:
Thomson Industries
Phone: (540) 633-3549
www.thomsonlinear.com

Igus

DEVELOPS EXCHANGE BEARING FOR LINEAR GUIDES

Igus has developed an exchange bearing for its drylin W linear guides that allows for swift replacement in high-frequency applications.

To execute the exchange, users simply unlock the bearing, push out the old liner and replace it. The exchange bearing saves time and cost, and is available in sizes 16 and 20 for linear guides on the drylin W series, besides the standard installation size 10.



The lubrication-free, corrosion-resistant liners are made of high-performance polymers for silent and precise sliding of linear guides. Igus, the Germany-based manufacturer of motion plastics, runs its North American operations out of Providence, R.I.

Swift and easy replacement

In extreme circumstances, abrasive sand or glass dust can cause wear of the liners on the linear guide rail. Linear guides and axes are also used in round-the-clock operation in automation equipment.

To replace liners previously, the entire linear carriage needed to be slid off the rail. Especially for linear axes or multi-axis linear robots with belt drives, this could only be done through costly disassembly and recommissioning.

The new exchange bearing, made with Igus' iglide J200 material, enables easy replacement directly on the linear rail in a few simple steps. The bearing reduces downtime, saves set-up costs and ensures 24/7 operation.

A practical, free tool enables safe installation of the liners in very little time. The new bearing is available for installation sizes 16 and 20, in addition to installation size 10, to enable even more users to take advantage of the new practical and efficient bearing. Linear robots, linear axes and drylin W linear guides can thus be easily retrofitted.

A few simple steps

Replacing the bearing is simple: First, users loosen the side cover of the linear housing with a screwdriver. With the free tool supplied, which the users can also 3D print, the liner can now be slid out of the housing and directly removed from the rail. The new lining made of the wear-resistant and abrasion-resistant high-performance plastic iglide J200 is then clipped onto the rail and inserted into the carriage with the mounting tool.

Users then put the side cover back on the linear housing and the bearing change is finished in no time. With this simple step, the rail is not damaged and the bearing housing can be reused without disassembly of belts or lead screws.

A pin located in the middle of the side cover secures the liner in the linear housing. Alternatively, replacement can also be executed with a screwdriver. On the new liner and in the carriage, igus has provided special recesses for this purpose.

The drylin W exchange bearing including mounting tool can be ordered online along with a practical retrofit kit with replacement liners, lid and mounting tool.

For more information:
Igus Inc.
Phone: (800) 521-2747
www.igus.com

LM76

LINEAR BEARING/PILLOW BLOCKS CAN BE USED IN RADIOACTIVE ENVIRONMENTS

LM76 now offers one piece ETX Linear Bearing/Pillow Blocks that will not degrade in a radioactive environment. Machined from a solid block of self-lubricating ETX, linear bearing-blocks have high strength, excellent wear resistance, low coefficient of friction, and excellent dimensional stability at higher temperatures As there is no other materials such as PTFE seals or lubricants these bearing-blocks are maintenance free. Custom designed for use in a nuclear power plant these linear bearing/pillow blocks travel on ceramic coated shafting (also supplied by LM76) completely submerged in radioactive water. Designed with a slight interference fit between bearing ID and shaft, contaminates are scraped from the shaft's surface. The low frictional characteristics of ETX have little impact on drive force. They are now available in inch and metric sizes.

ETX bearing-blocks are also FDA/USDA/3-A Dairy compliant and are also are ideal for: Pharmaceutical, medical, food, and dairy processing applications.

EXT features a high continuous service temperatures up to 210°F (100°C) and offers good chemical and abrasion resistance, low moisture absorption, and resistance to staining. These ETX linear bearing-blocks with the slight interference fit keeps the bearing free from debris and bacterial contamination, are not affected by biological fluids, mild acids, can be washed down with cleaning agents, and steam cleaned.

Don't need solid EXT bearing-blocks consider the FDA/USDA/3-A Dairy compliant electroless nickel coated or stainless steel pillow blocks with PTFE linear bearings and Snap-in EXT Scraper Seals which are available for closed linear bearings, and closed pillow and flange blocks.

For more information:
LM76
Phone: (413) 525-4166
www.lm76.com

Applied Motion Products

EXHIBITS SERVO MOTORS, SERVO DRIVES AND STEPPER DRIVES AT AUTOMATE 2019

Applied Motion Products will demonstrate a selection of new integrated motors and drives for both servo and stepper motors in Booth #8147 at the Automate Show to be held at McCormick Place, Chicago, Illinois, April 8–11, 2019

Products on display will include the following:

MDX Integrated Servo Motors that combine high torque density, low inertia servo motors with on-board drives and controllers to create all-in-one integrated motor solutions that save on space, wiring, and cost over conventional servo systems with separate motor and drive components.

StepSERVO Integrated Motors that provide cost-effective and high-torque motion control for high throughput applications such as packaging and labeling, automated test and measurement, and automated assembly.

STF Stepper Drives that support a range of industrial Ethernet and Fieldbus network protocols including EtherCAT, EtherNet/IP, CANopen, Modbus, Ethernet and RS-485, as well as a proprietary Serial Command Language (SCL) for efficient network communications over Ethernet (UDP or TCP) and RS-485. Using STF Stepper Drives, system designers and machine builders have the flexibility to control step motors using the network protocol of their choice.

SV200 Digital Servo Drives that operate on 24, 48 or higher DC supply voltages for space-constrained and multi-axis motion control applications.

For more information:
Applied Motion Products
Phone: (831) 763-5933
www.appliedmotion.com

Intellidrives

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Direct drive rotary servo tables feature IP rated ingress protection. IP rating assures against ingress of water and external particles. IP65 rating assures against ingress of dust and small water jets. IP66 rating assures, in addition to IP65, against ingress of powerful water jets. IP67 rating assures, in addition to IP66, against water penetration under heavy water jets and when partially submerged.

Direct Drive rotary tables provide superior angular positioning and are designed to eliminate backlash, friction and wear problems associated with worm, gear and belt drives. Low maintenance and high throughput characteristics of the DDR stages yields the lowest total cost of ownership. These rotary tables utilize direct drive three phase brushless motor technology. There are no brushes to replace and no gear trains or belts to maintain.

Accurate Positioning performance is assured with precision Absolute encoder that provides arc-sec positioning resolution. The motor and rotary encoders are directly coupled to eliminate coupling backlash. Absolute encoder keeps track of its position at all times, and provides it as soon as power is applied. This feature is particularly useful in applications where the equipment has power turned off between uses. No need to move to home sensor or index pulse to establish a reference position.

For more information:
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DieQua

PROMOTES LATEST TECHNOLOGIES AT ATX WEST

The 2019 ATX-West exposition featured more than 2,000 cutting-edge manufacturers that attracted over 20,000 attendees looking for the latest in motion control, robotics, inspection, and automation control solutions. Over the course of the three days, the following products were present at the DieQua booth: Precision servo worm gearheads, rotary flange servo gearheads, zero backlash cycloidal reducers, hypoid servo reducers, low backlash spiral bevel gearboxes and screw jack actuators. This year, the additional piece to DieQua's booth was the Tri-Bot. This robot contained three Sesame Motors that were used for each arm of the machine. This machine was able to move ping pong balls in a pattern. **PTE**

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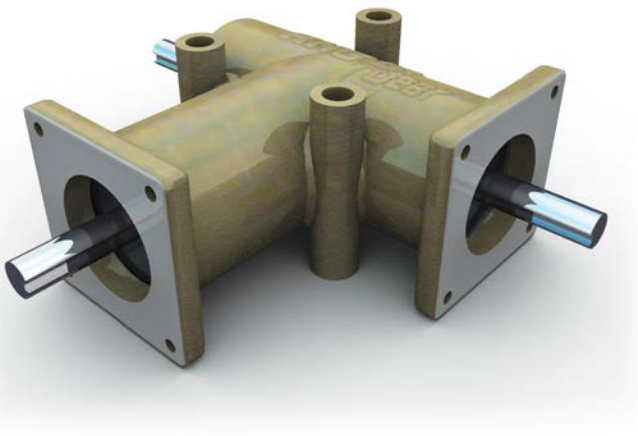
Andantex USA

Anglgear™: Made in the USA, Powering Industry Worldwide

Andantex USA's objective over the years has always remained the same: to provide innovative, high-quality gearboxes and solutions for use on industrial machinery. The Anglgear™ right angle drive is an example of our commitment to our customers' needs and applications. Since purchasing this product line more than 30 years ago, the Anglgear has grown into a product that is now used in various applications across the printing, converting, packaging, general purpose and aerospace industries.



In addition, we also supply all branches of the military, conforming to contracts specifying various MIL SPEC requirements.

The Anglgear™ line consists of 14 different models available from stock in both an Inch and Metric series and sold worldwide. ***We take pride in the fact that all Anglgear drives are assembled and shipped from our headquarters in New Jersey. Here, we manufacture, and inspect every unit that goes out the door. This ensures consistent quality in all our gearboxes.***

Our standard units are available from stock in 1:1 and 2:1 ratios, with 2 shafts or 3, 2 flanged or 3 flanged units, and are lubricated for life before being shipped.

Over the past 10 years, we have seen that a huge part of our growth in this line is due to the fact that we will modify our units to meet our customers' design specifications. **It doesn't matter if it's a one-piece special order or a quantity order;** our engineers will work with our customers to give them the best solution for their application and needs.

Examples of our modifications include various shaft lengths and configurations, including shafts with flats, splines, holes, etc. We also offer 3-way units with counter-rotating output shafts, as well as custom housings with flanges and bosses removed for custom mounting applications, special materials, bearings, seals and epoxy coatings as needed. We can provide units with special backlash upon request, and offer various options for grease including food grade, high temperature and radiation resistant.

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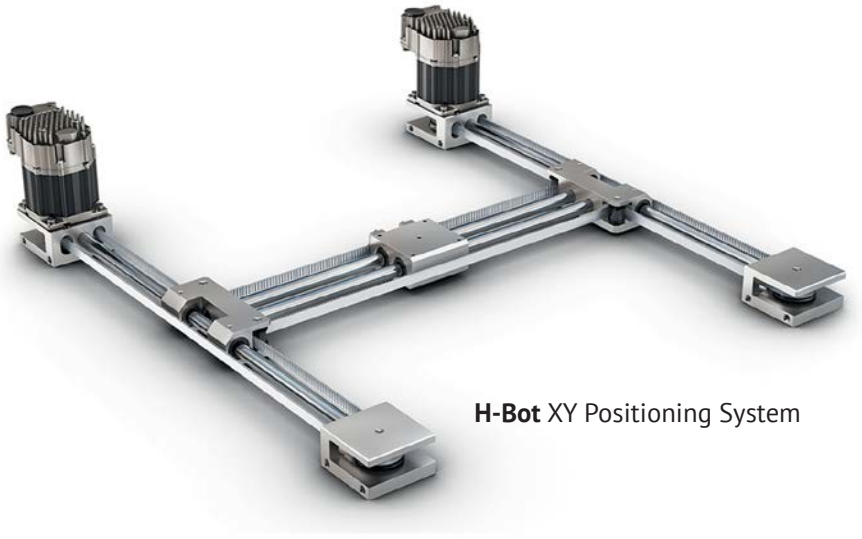
Schaeffler Group USA Inc.

Schaeffler Engineering: Greater Than the Sum of Our Parts

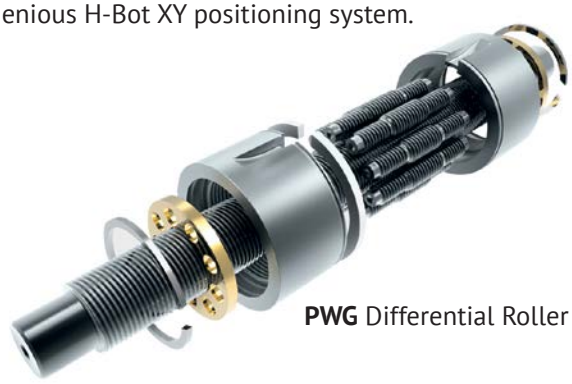
The Schaeffler Group is a leading global automotive and industrial supplier whose enduring success is built upon outstanding technology and a singular innovative ability. Over 92,000 employees make Schaeffler one of the world's largest technology firms in family ownership, encompassing a worldwide network of manufacturing plants, R&D facilities and sales companies at approximately 170 locations in over 50 countries. With a complete line of bearing solutions for a wide range of industrial applications as well as high-precision components and systems for engine, transmission and chassis applications, the Schaeffler Group is actively shaping "Mobility for Tomorrow."



H-Bot XY Positioning System

In addition to rolling bearings for practically any application, linear bearings and guidance systems are a vital part of Schaeffler's product portfolio. Unrivaled in scope and versatility, Schaeffler's linear product lineup ranges from shafts with linear ball bearings and monorail guidance systems to sophisticated actuators with drives and control systems, plus special coatings and every conceivable accessory.

But that's only the start. Schaeffler's linear portfolio is based on a modular concept that goes far beyond mere components. We can design a complete system solution tailored to the customer's specific application—from large gantry robots to intricate circuit board inspection systems. In fact, many of our linear guidance systems started out as solutions to customers' needs! Case in point: Schaeffler's ingenious H-Bot XY positioning system.



PWG Differential Roller Screw

Sometimes, of course, a Schaeffler solution comes about because a customer's needs were not being met by the conventional standard. Such is the case with Schaeffler's innovative PWG differential roller screw. Within the pantheon of traditional mechanical/linear drive systems, the screw category has been limited to lead screws, ball screws and roller screws.

Until now.

In response to a customer's request for a solution that better addressed its ambitious price-performance target, Schaeffler developed the PWG differential roller screw as a new option that offers the high forces of a traditional roller screw, but at a price point closer to a ball screw.

So, while innovative products make up the heart of Schaeffler's offerings to our customers, service represents the soul of what we do. Because when it comes to linear guidance systems, Schaeffler has all the pieces – all you have to do is supply the puzzle. Together, we'll create the perfect linear solution… yours!

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Making Sense Out of Autonomous Vehicles

The Role of Lidar Technology in the Automotive Industry Today

Matthew Jaster, Senior Editor

An argument can be made that the sensor has had one of the greatest impacts in manufacturing in recent years. Need proof? You can't have a discussion about Industry 4.0 or the Industrial Internet of Things (IIoT) without mentioning how sensors placed inside components or machinery are changing the way shop floors operate today.

It's happening everywhere—from automation technology to aircraft production to even keeping tabs on the health of human beings. Sensors are working in conjunction with cameras, analysis software and robotics to provide real-time monitoring in a wide variety of industries. Autonomous vehicles (AVs), in particular, are set to utilize sensors for a multiple array of new technologies. In fact, lidar sensors may be the key to unlocking the potential of driverless cars in the future.

According to **Dr. Mircea Gradu**, vice president quality and validation at Velodyne Lidar, Inc. both the AV and lidar sensor industries are very young and extremely competitive.

"Time to market is extremely important, and given the historically longer duration required to develop standards for testing and validation along with a meaningful regulatory frame, these steps take a lower priority for some of the players," Gradu said "Velodyne is a strong voice within the industry promoting the safe deployment of AVs, including their comprehensive testing and validation based on a common set of real world scenarios and relevant corner cases."

Velodyne Lidar is currently working with industry representatives, academia and lawmakers to determine how lidar sensor technology can impact the automotive industry of the future. The end game is a self-driving automobile ride that will take passengers to their required destinations safely, comfortably and efficiently. While the secret to the AV industry's success may rest on many factors, sensor technology continues to play a key role in its development.

Velodyne Lidar is working with industry representatives, lawmakers and academia to determine how lidar sensor technology can impact the automotive industry.

An Overview of Lidar Sensors

The term lidar was originally created by combining the words "light" and "radar." Later, the interpretation of lidar became an acronym for (light detection and ranging), a surveying method that measures distance to a target with pulsed laser light and then measures those reflected pulses with a sensor.

The technology is commonly used to make high-resolution maps, conduct atmospheric research and meteorology, and is being utilized by agricultural robots for seeding and fertilization. It was identified by NASA as a key technology to enable the safe landing of future robotic and crewed lunar-landing vehicles (it's the same technology used today when a cop is pointing a lidar gun toward your vehicle to see how fast you were going).

The concept of lidar technology dates back to the 1930s. The technology was developed further in the early 1960s, closely following the invention of the laser. Lidar gained public notice in 1971 when the Apollo 15 mission used the technology to map the moon's surface. Since then, this technology has been deployed in applications such as self-driving cars, unmanned aerial vehicles, robotics, security, and more.

Developing High-Performance Sensor Solutions for the AV Industry

You may have heard a news story or two in recent years about self-driving cars. They're coming. Frankly, the technology is already here. In 2019, it's really more about examining and testing these autonomous transportation methods in order to ensure vehicle and passenger safety and to develop electronic systems that deliver driver assistance.

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Lidar systems play a crucial role in in areas like Adaptive Cruise Control (ACC), Automatic Emergency Braking (AEB) and Lane Keep Assist (LKA). These functions depend on the detection of a vehicle's environment to act autonomously or semi-autonomously. Lidar mapping and estimation achieve this.

Velodyne Lidar provides smart, powerful lidar solutions for autonomy and driver assistance. Founded in 1983 and headquartered in San Jose, California, Velodyne is known worldwide for its portfolio of lidar sensor technologies. In 2005, Velodyne's founder and CEO, David Hall, invented real-time surround view lidar systems, providing perception and autonomy for automotive, new mobility, mapping, robotics, and security applications.

This technology was developed as part of the Defense Advanced Research Projects Agency (DARPA) Grand Challenge, a prize competition for American autonomous vehicles funded by DARPA to sponsor research that bridges the gap between fundamental discoveries and military use. Hall first developed vehicle software and hardware in 2004 as part of the competition. For the last 15 years, the company has continued to move this sensor technology forward adding intelligence and enabling customers to detect more objects and offer cars a more detailed view of their surroundings.

According to Gradu, Velodyne organizes The World Safety Summit annually, a forum for bringing together the industry representatives, OEMs and Tier suppliers, law makers and academia to work toward a non-competitive, shared information approach on safety topics, similarly to the one embraced by the aircraft industry decades ago. It's these shared experiences and collaborations that will help AV fleets become the norm in the coming years.

"To achieve the necessary safety requirements in the AV industry, we're going to need sensor development that is done in conjunction with a universal standard. This includes testing, validation, calibration, simulation, and software/hardware that work together seamlessly," Gradu added.

Technology Update in Munich

Gradu recently spoke about the technology during the 2019 International VDI Conference – Automotive Sensor Systems in Munich, Germany. During the event, attendees heard an overview on advanced lidar solutions, along with a look at market segmentation and specific requirements for lidar.

Gradu addressed key considerations in lidar component testing and system validation. He also examined safety and standardization implications for lidar in providing advanced driver assistance capabilities, such as Lane Keeping Assist (LKA), Automatic Emergency Braking (AEB), and Adaptive Cruise Control (ACC).

To help conference attendees learn about driver assistance systems, Velodyne and the International VDI Conference have posted a white

In order to achieve the necessary safety requirements in the AV industry, sensor development must be done in conjunction with a universal standard.

paper on driver assistance technology on the conference website. The paper discusses the levels of vehicular automation defined by the Society of Automotive Engineers (SAE) International, the advantages of lidar sensors, and how lidar enables a safety-first approach that provides significant advances in driver assistance.

Download the white paper here: (*www.vdi-wissensforum.de/en/event/automotive-sensor-systems-2019/*)

Gradu's session at the VDI Conference was called "Advanced Safety Lidar Solutions and Opportunities in their Testing and Validation."

He received extremely positive feedback on the presentation with several of the participants (OEMs and Tier 1s) enlisting their teams to join the efforts toward the standardization of the test and validation protocols for AVs at the complete vehicle system level, as well as sub-system and component level.

In addition, SAE International sponsored an Edge Report on "Unsettled Topics Concerning Sensors for Automated Road Vehicles," that included Velodyne CTO's Anand Gopalan's direct input, summarizing how the AV community plans to address these issues in a timely manner.

The SAE Edge Research Report identifies key unsettled issues of interest to the automotive industry regarding the new generation of sensors designed for vehicles capable of automated driving. Four main issues are outlined that merit interest:

First, specifying a standardized terminology and taxonomy to be used for discussing the sensors required by automated vehicles.

Second, generating standardized tests and procedures for verifying, simulating, and calibrating automated driving sensors.

Third, creating a standardized set of tools and methods to ensure the security, robustness, and integrity of data collected by such sensors.

The fourth issue examines the ownership and privacy of data collected by automated vehicle sensors.

All of these issues must be examined and addressed in the coming months to move AV technology forward.

A Growing Market

Velodyne is working with a growing number of companies on sensor technology including Ford, Mercedes Benz, Volvo, TomTom, Here, Bing and others.

"Velodyne has over 100 customers representing traditional automotive OEMs, AV technology companies, commercial and off-highway vehicle manufacturers, as well as a wide variety of players from the aircraft, aerospace, drone, naval and security industries," Gradu said. "Velodyne's experience on all early AV prototypes allowed us to gather invaluable knowledge related to real world operating conditions and representative scenarios for the sensor validation."

Gradu said there is unanimous agreement that lidar is, and will remain, a vital component of the AV system in particular for Level 4–5. The leading edge technology advancements introduced by Velodyne within the new Alpha Puck, Velarray, and VelaDome products are focused on the

highest range and resolution performance, enhanced near field capability, power consumption reduction, weight, volume and cost optimization will position the lidar technology even stronger in the AV space.

"Companies in the autonomous space need to work together – just as companies in the aerospace industry cooperate on safety issues – in order to ensure the safe launch of AVs," said Gradu. "Velodyne is committed to fostering this industry learning experience to apply rigor into sensor validation, especially in addressing corner cases that present high safety risk."

While sensor technology will be crucial to the success of the AV industry, Gradu believes lidar technology is merely scratching the surface and will be able to offer self-driving vehicles further advancements in the coming years. Both *Gear Technology* and *Power Transmission Engineering* will report on these developments in future issues.

"How will a driverless car decide the optimal path for the vehicle to take in the future?" asks Gradu. "And what can we do to optimize areas like performance, comfort and the powertrain by utilizing unique sensor technology in these vehicles? These are the types of questions we're asking."

For more information:
Velodyne LIDAR
Phone: (408) 465-2800
www.velodynelidar.com

Velodyne's product portfolio offers an entire range of lidar solutions for AVs and advanced driver-assistance systems (ADAS), providing the real-time perception data that enables safe and reliable operation. The company produces both directional and surround-view sensors. The computer perception data provided by these sensors allows immediate object and free space detection for safe navigation. In recent months the blog on the Velodyne website has examined how many of the features of lidar sensors can impact a driverless car in terms of resolution, range and field of view.

Resolution

High-resolution lidar is critical for object detection and collision avoidance at all speeds. Finer resolution allows a sensor to more accurately determine the size, shape, and location of objects, with the most advanced lidar sensors being able to detect objects within three centimeters and some moving closer to two centimeters. This finer resolution outperforms even high resolution radar and provides the vehicle with the clearest possible vision of the roadway.

To examine the importance of resolution, consider the example of a tire fragment in the road. The lidar system needs to be able to not only detect the object but also recognize what it is. This is not an inconsequential task given that it requires detecting a dark object on a dark surface, so a sensor with finer resolution increases the vehicle's ability to accurately detect and classify the object. To aid the process of responding to roadway events, unlike cameras, lidar provides 3D images of the surroundings with precise measurements of how far away objects are from the vehicle.

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Range

Lidar range is a topic that creates significant buzz in the auto industry. Autonomous vehicles need to see as far ahead as possible to optimize safety. At highway speeds, a minimum range of 200 meters allows the vehicle the time it needs to react to changing road conditions and surroundings. Slower, non-highway speeds allow for sensors with shorter range, but vehicles still need to react quickly to unexpected events on the roadway such as a person focused on a cellphone stepping onto the street from between two cars, an animal crossing the road, an object falling from a truck, and debris ahead in the road. In each of these situations, onboard sensors need sufficient range to give the vehicle adequate time to detect the person or object, classify what it is, determine whether and how it is moving, and then take steps to avoid it while not hitting another car or object.

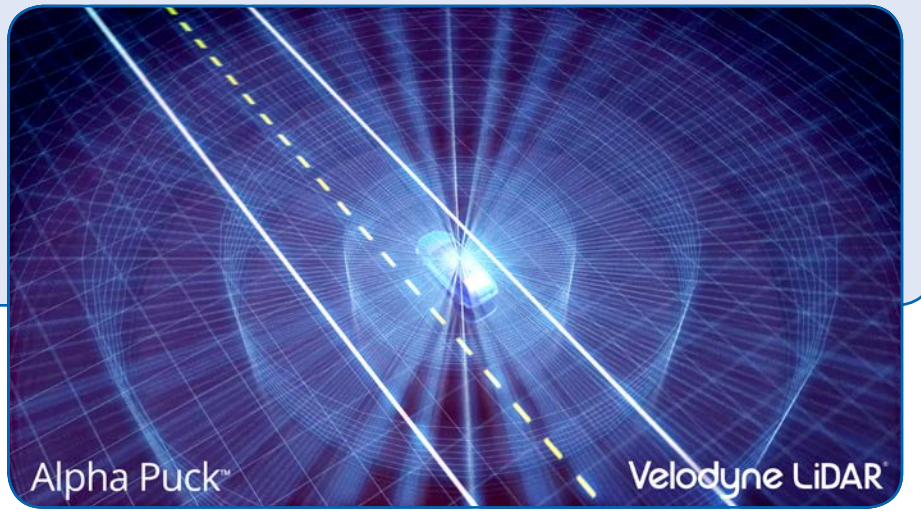
Another factor connected to range is reflectivity. Reflectivity refers to an object's propensity to reflect light back to the sensor. Lighter colored objects reflect more light than darker objects. While many sensors are able to detect objects with high reflectivity at long range, far fewer are able to detect low reflectivity objects at range.

Field of View

It is widely accepted that a 360° horizontal field of view – something not possible for a human driver – is optimal for safe operation of autonomous vehicles. Having a wide horizontal field of view is particularly important in navigating the situations that occur in everyday driving.

For instance, consider the scenario of performing a high-speed merge onto a highway. The maneuver requires a view diagonally behind the autonomous vehicle to see if another car is coming in the adjacent lane. This also requires a view roughly perpendicular to where the vehicle is currently traveling to assess cars in the adjacent lane and confirm there is room to merge. Throughout this process, the vehicle must look forward so it can negotiate traffic ahead of it. For these reasons, a narrow field of view would be insufficient for the vehicle to safely execute the merge maneuver.

Therefore, lidar sensors that rotate are optimal for these applications because one sensor is capable of capturing a full 360 degree view. In contrast, if an autonomous vehicle employs sensors with a more limited horizontal field of view, then more sensors are required and the vehicle's computer system must then stitch together the data collected by these various sensors. (*www.velodynelidar.com/newsroom/category/blog/*)



Insider's Guide to Automate 2019 and Promat

Automate Show Examines the Integration of Robotics, Automation and Machine Vision, while Promat explores the latest in material handling technology

Matthew Jaster, Senior Editor

Technology is turning itself upside down and inside out all in the name of productivity and efficiency. If you don't know how to leverage your artificial intelligence or make use of IIoT on your shop floor, you're not alone. There's a lot going on behind the scenes in motion control, robotics and industrial automation today. Automate 2019 is the biennial trade show that provides the full spectrum of automation technologies and product demonstrations that will help attendees solve today's greatest manufacturing challenges. Here's a brief rundown of what to eWxpect at McCormick Place in Chicago from April 8–11:

Changing Technologies

Mobility, smart manufacturing and energy efficiency are key areas for Automate 2019. Along with the latest and greatest products available to make industrial automation better, there's a strong push to help manufacturers understand how to get started by adding robotics and automation to their operations.

"There are plenty of new technologies launching this year that we didn't see at the show in 2017," said Bob Doyle, vice president of the Association for Advancing Automation (A3). "The biggest emphasis is mobility, specifically mobile robotics utilized in warehousing and on the manufacturing floor. Artificial intelligence is another focal point and how it can be utilized to improve a manufacturers' operation."

Collaborative robots have been around awhile now, but according to Doyle they are entering new markets and providing unique opportunities for small to medium-sized manufacturers that may have never automated before.

"How do I get started in automation? Where do I begin? These are the questions being asked. We're finding as we work with our member companies that they're still very new to many automation and motion control concepts, but they know that they have to get ahead and prepare their manufacturing floors for these critical advancements. This is why 'Win the Future!' is the tag line for this year's show," Doyle added.

This is why Automate 2019 features system integrators at the front of the exhibition hall. "Manufacturers can come see the system solutions available to the end users right when they walk in," Doyle said. "This is beneficial for companies that have never automated before as well as companies that may have *some* experience with robotics and automation, but will have the benefit of seeing the latest technologies first-hand."

Education First

The paid conference at Automate 2019 includes a full schedule of speakers on a variety of technical subjects including "How to Automate," where Doyle said attendees can come for a day and learn the ROI of automation, how to get involved in robotics, machine vision, motion control, etc. All the categories A3 represents. Additional conference tracks are available on automation solutions, collaborative/mobile robots, AI, digitalization, smart manufacturing and more.

There are also educational opportunities available on the exhibit floor free to attendees including topics on robotic integration, investing in automation and workforce development.

"We will be having discussions on workforce development on the last day of the show and what the industry needs to do to prepare the next generation of workers for the future," Doyle said. "It's the same day we invite college and high school students to see the benefits of automation and robotic careers."

A Trend for Robotics in General Manufacturing

In the past, the automotive industry has typically been where the majority

of robotics is being utilized, but lately these figures are starting to change course. Based on statistical input from 2018, robotic sales in general industry—outside of automotive—are starting to catch up.

"You can look at this statistic a couple of ways. Automotive sales for robotics are down. We knew this was going to happen. Since the end of the great recession in 2010/2011, robotic sales in the automotive industry had been going gangbusters. We knew there had to be a slowdown. It's a very cyclic industry," Doyle said. "However, with the rise in areas like gripping technologies and collaborative robots, more and more non-traditional industries are seeing the benefits of robotics and automation today including food and beverage, plastics, aerospace and laboratory/bio applications. So when things start to slow down in one industry, we see significant growth in others."

Smart Growth

Automate 2019 also hopes to help companies answer the question "What does smart manufacturing mean to me?" Industry 4.0, IIoT or whatever the latest buzzword may be really comes down to making your shop more efficient. Doyle believes it's simply a way to use data to better manage your day-to-day operations.

"Smart manufacturing is basically just an extension of the old tried and true formula of a quality board or throughput board hanging in the shop floor that tells you how many pieces went through the factory in the last hour. This is really about using collected data to make your operation better. The only difference in 2019 is that with sensors and monitoring devices there is so much more data available to all of us."

FANUC has a zero downtime initiative that they launched at General Motors, for example. They have the ability to monitor their equipment remotely and make sure that everything is functioning optimally. Learn more here: *www.fanucamerica.com/products/robots/zdt-zero-down-time*. This is where Doyle believes the industry is moving, a connected factory floor that provides greater value in areas like preventative maintenance and condition monitoring.

Promat 2019: Material Handling Solutions

Promat has been a great partner with Automate since 2011. The collocated exhibition offers the latest on manufacturing, distribution and supply chain equipment and systems. It features more than 1,000 solution providers, 100+show floor seminars and new town hall style sessions on emerging technologies. "The automation solutions we offer and the material handling solutions they offer are a great fit," Doyle said. "We look forward to continuing the successful partnership in the future."

Launch Startup Competition

The Launch Startup Competition gives the industry's most innovative young companies the chance to vie for a $10,000 cash award and the spotlight at Automate 2019.

"Startups continue to play a critical role in the ongoing development of automation technology, and this competition lets us identify and support them by providing a cash award while getting them in front of industry leaders, potential partners and investors that can help them along the way," said Jeff Burnstein, president of A3. "If the past is any indication, we expect to see many of these finalists go on to transform the manufacturing and services sectors over the next decade."

Companies entering the Automate Launch Pad Startup Competition must have launched in the last five years, raised less than $5 million since creation and not be affiliated with a larger group. Seven finalists will compete for the top $10,000 prize at Automate 2019 on April 10 at 3:00 pm, where they will have three minutes to pitch their technology solution to a panel of judges. All finalists will also be awarded 10 ft. × 10 ft. booth space at Automate, giving them the opportunity to engage with over 20,000 expected attendees.

"We really started to see interest in robotic investments around the time we created the Launch Startup Competition in 2015," Doyle said. "The 2015 winner was a startup company from Boston called Soft Robotics. Since they won the competition the company has grown to 50+ employees and their booth at Automate continues to get bigger at each show."

The Future of Automate

Doyle says upcoming shows will focus on mobility. "There will be a lot of opportunity for robotic arms on mobile platforms. I also believe we'll see more opportunity for non-traditional industries to utilize robotics and automation," Doyle said. "Hopefully, it will be put to rest the idea that robotics and automation take jobs away. We've been fighting this fight for a while now and we see it finally turning a corner. This is about how automation and robotics can improve a manufacturing operation and, in turn, increase their success and job growth."

Doyle believes the show will also start to crossover to residential use in the future. "We will probably start to crossover to the home, service robots for an elderly person, for example. The joke at the moment is that the only successful service robot in the home is the Roomba. This is going to change in the coming years. There's a great opportunity for expansion, maybe in ten years we'll see a more general audience interested in a show like Automate."

For more information:
Automate 2019
Phone: (734) 994-6088
www.automateshow.com

Booth Previews

Heidenhain Corporation

BOOTH #8346

Heidenhain is proud to take part in the Automate 2019 show at McCormick Center in Chicago, IL from April 8th–11th.

Heidenhain will be highlighting its next generation condition monitoring system, ADS Uptime, from the brand Leind and Linde. Encoders with built-in ADS Uptime will enable system monitoring of the most relevant data from rotary installations and motors. ADS solutions will naturally simplify the move from preventive maintenance, to start practicing proactive maintenance. ADS Uptime will also feature wireless service check-up via Bluetooth. The wireless service check-up will facilitate maintenance, but also drive system management, production planning and operation.

In addition to the Leine and Linde products, Heidenhain will also be featuring products from their other brands like Etel, Renco, and LTN as well as displaying the newest available rotary and angle encoders from Heidenhain.

Etel is an international supplier of direct drive linear and torque motors, motion control components and integrated systems. Their TMB+ torque motor is one of the highest performing direct drive motors on the market providing optimal density with an expansive variety of available sizes.

Renco is a well-known brand focused on providing compact yet powerful rotary encoder solutions. They use the optical scanning principle and offer the greatest possible functionality while featuring the smallest possible dimensions, thanks in large part to their simple and self-centering installation method with the patented slide-lock mechanism. This makes them particularly suitable for operation in electrical drive technology, robotics, medical technology, automation, and building services engineering.

LTN specializes in providing slip ring and resolvers to international machine builders and factory automation industries. Their newest Fiber Optic rotary slip rings are capable of handling 4K transmissions with an extremely low loss rate and are well positioned to handle the next step in video and signal transmissions.

For more information:
Heidenhain Corporation
Phone: (847) 490-1191
www.heidenhain.us

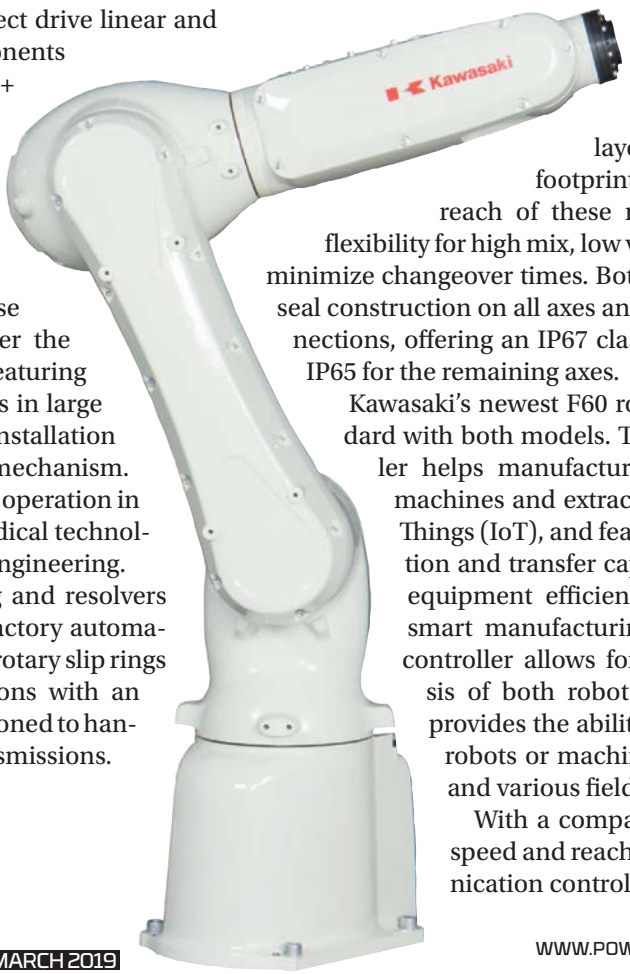
Kawasaki Robotics (USA), Inc.

BOOTH #7340

Kawasaki RS007N and RS007L robots

In response to the rising demand for fast, flexible and compact industrial robots in food and other industries, Kawasaki developed two 6-axis vertically articulated robots with a maximum payload capacity of 7 kg and different reach. The RS007N and RS007L models are the latest additions to the company's general-purpose R series line of small-to-medium payload (3–80 kg) robots ideal for a wide range of applications including packing, material handling and machine tending.

The Kawasaki RS007N and RS007L robots continue to offer the operational advantages of the R series robots while incorporating a newly redesigned arm structure and main-unit weight reductions. By redesigning the arm structure and adjusting the acceleration rates in accordance with load weights and robot positioning, the RS007N and RS007L models offer consistently optimized performance by significantly reducing cycle times. These enhancements also result in the fastest operating speeds in these robots' class (12,100 mm/s) along with increased working ranges.



The RS007N robot features a 730 mm reach and the RS007L a 930 mm reach for greater flexibility in production facility layouts. The small installation footprint and greater speed and reach of these robots provide automation flexibility for high mix, low volume production, and can minimize changeover times. Both models feature a double-seal construction on all axes and waterproof electrical connections, offering an IP67 classification for the wrist and IP65 for the remaining axes.

Kawasaki's newest F60 robot controller comes standard with both models. This state-of-the-art controller helps manufacturers digitally connect their machines and extract value from the Internet of Things (IoT), and features enhanced data collection and transfer capabilities to support overall equipment efficiency (OEE) calculations and smart manufacturing. The Bluetooth enabled controller allows for the collection and analysis of both robot and production data and provides the ability to link to the cloud, other robots or machines, tablets, vision cameras and various fieldbuses.

With a compact design, industry leading speed and reach, and an enhanced communication controller, the RS007N and RS007L

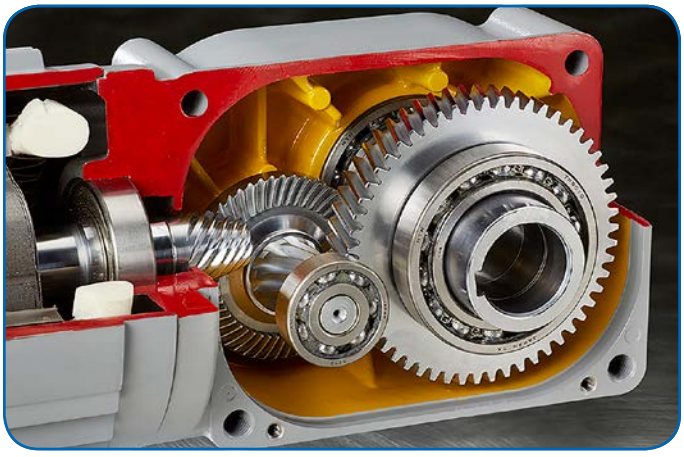
robots meet the demand for smart and flexible manufacturing, enabling efficient small batch production and minimizing changeover times.

For more information:
Kawasaki Robotics
Phone: (248) 446-4100
www.kawasakirobotics.com

Brother Gearmotors

BOOTH #N6219 (PROMAT)

Brother Gearmotors, a division of Brother International Corporation that offers a wide range of ultra-reliable, sub-fractional AC gearmotors and reducers for the food & beverage, packaging and material handling industries, will use Promat 2019 as the opportunity to introduce a best-in-class five-year warranty for all standard products. The lengthy guarantee solidifies Brother's commitment to producing only the highest quality gearmotors and reducers and represents the longest, most comprehensive warranty in the industry. The five-year warranty shows Brother Gearmotors' confidence in the



effectiveness and durability of its wide range of products. In the U.S., Brother Gearmotors parts are distributed and serviced from its centrally-located plant in Bartlett, TN. In addition to offering quick delivery, the state-of-the-art facility features on-site technology that not only provides expedited shipping, but also offers accessorizing and customizing for gearmotors such as sprockets, pulleys, connectors, extension cables and custom labeling.

For more information:
Brother Gearmotors
Phone: (866) 523-6283
www.brothergearmotors.com

Promess, Inc.

BOOTH #9219

Promess, Inc. manufactures turnkey monitoring and motion sensing systems for precision assembly and test applications based on a series of standard hardware components synchronized, controlled and monitored with sophisticated programmable electronics and specialized proprietary software. They will exhibit four system "building block" technologies in Booth 9219 at Automate 2019 in Chicago April 8–11.

On display will be the new Promess PRO-Bot2x two-axis part-positioning arm with Joined Axis technology, the Promess Electro-Mechanical Assembly Press (EMAP), the Promess TorquePRO Torque Assembly System and the Promess Rotational Electro-Mechanical Assembly Press (REMAP). These four products may be used individually to perform discrete assembly functions, or combined into sophisticated, multi-function assembly and test systems.

Promess PRO-Bot2x

The PRO-Bot2x is a precision part-positioning arm which can position parts for safely loading and unloading. The Pro-Bot2x can handle up to 500kN of load when it is not moving. It is designed to bridge the gap between manual and fully automated operations in press applications by providing accurate movement between manual or robotic load/unload stations and multiple press locations utilizing Joined Axis technology. A single Promess UltraPRO controller can be used to control both the PRO-Bot2x and the press operations to simplify operational integration.

Promess EMAP

The EMAP is a fully electric, servo driven ball screw press with integrated motion control and monitoring for force, position and other application parameters as required for in-process verification and monitoring. Promess EMAPs are available with capacities from less than one ounce to more than 200,000 pounds.

Promess TorquePRO

The TorquePRO is a fully electric, servo driven unit that electronically monitors up to 15,000 Nm of torque and angular position in real-time using a closed-loop feedback system. The TorquePRO can move to an angle, move to a pre-

set torque, move to multiple positions and/or torques, and hold a constant torque all using completely programmable parameters

Promess REMAP

The REMAP combines precise, fully programmable control of linear and rotary motion in a single unit using built-in force and torque sensors. It is programmable for position, velocity, acceleration, angle, angular velocity and angular acceleration using both relative and absolute limits. Applications include pressing to position, pressing to a programmed force, turning to an angle and turning to a predetermined torque all with real-time feedback.

For more information:
Promess, Inc.
Phone: (810) 229-9334
www.promessinc.com

Beckhoff Automation

BOOTH #S-4512 (PROMAT)

Beckhoff Automation will show multiple new technologies that bolster material handling and logistics operations at Promat 2019 in Chicago. The North American product debuts include the ultra-compact CX7000 embedded controller and a preview of EtherCAT G gigabit industrial Ethernet technology. The trade show will also find the latest innovations in space-saving distributed servo drive technology and flexible TwinCAT 3 automation software at the Beckhoff booth.

Expanded EtherCAT offerings on display will include the EK1000 EtherCAT TSN Coupler and innovative EtherCAT G offerings. The EtherCAT TSN approach will assist distribution centers in the implementation of real-time systems. Ideal for new installations or retrofits, this flexible technology will keep pace with rapidly evolving networking methodologies in the material handling industry. Furthering this goal, Beckhoff also recently announced EtherCAT G and EtherCAT G10, which will provide communication at 1 Gbit/s and 10 Gbit/s, respectively, in conformance with the IEEE 802.3 Ethernet standard. An innovative branch controller model will enable the parallel operation of standard 100 Mbit/s segments with EtherCAT G or G10 as the main trunk, or vice versa, to provide the fast communication needed in today's distribution centers.

Scalable PC Control automates today's distribution centers

The recently introduced Beckhoff CX7000 embedded controller presents a compact yet powerful EtherCAT controller, boasting a single-core, 400 MHz ARM Cortex-M7 processor. The DIN rail-mountable controller maintains minimum footprint with dimensions of just 49 × 100 × 72 mm. Along with the ability to directly connect to the full range of Beckhoff EtherCAT I/O modules via a backplane, it has eight 24 V digital inputs and four outputs built into the device. With a low price point and the ability to leverage feature-filled TwinCAT 3 automation software, the CX7000 extends the range of Beckhoff controllers to include both ultra-compact controllers that can act as distributed control devices on the EtherCAT network across distribution centers all the way up to powerful many-core controllers capable of controlling entire warehouses.

Also appearing at Promat will be compact multicore automation solutions such as the C6015 Industrial PC (IPC) with an Intel Atom processor and the C6030 IPC available with Intel Core i-series processors. These are ideal for mid-range to complex machine control, but they can also be used for other functions such as edge computing and IoT gateway devices to connect existing systems to major cloud platforms, such as Microsoft Azure, Amazon Web Services (AWS) and SAP HANA. Both IPCs are among the fast-growing assortment of Microsoft Azure Certified industrial devices from Beckhoff.

Control solutions for every material handling application

Beckhoff will showcase many other exciting automation technologies at Promat for the first time. Increasing its IoT and smart factory offerings, Beckhoff will also display the latest solutions from TwinCAT Analytics and HTML5-enabled TwinCAT HMI software for industrial displays and mobile devices. In addition, surprise announcements are planned at Promat regarding updates to TwinCAT 3.

Other smart factory innovations will include the AMP8000 distributed servo drive system with One Cable Automation. Combining a servo drive and servomotor in one space-saving device enables enclosure-free motion control architectures. The system minimizes machine and equipment footprint while increasing cost effectiveness by integrating STO and SS1 motion safety functions. Additional savings are achieved through reductions in electronics, mechanical hardware and cabling through the EtherCAT P One Cable Automation solution available in AMP8000 and a wide range of Beckhoff I/O devices.

"With the unstoppable growth of e-commerce as driven by the continuing shift in consumer purchasing behavior, material handling and logistics operations have extra pressure to become faster and more reliable, and their

automation systems must support throughput and reliability improvements," said Doug Schuchart, material handling and logistics vertical market manager, Beckhoff Automation LLC. "From the new CX7000 controller to the sophisticated motion control of the AMP8000 to EtherCAT G and TSN-ready I/O solutions, the technologies Beckhoff will present at Promat are truly cutting edge. These, along with enhanced TwinCAT software capabilities, can boost competitiveness at any distribution center."

For more information:
Beckhoff Automation
Phone: (952) 890-0000
www.beckhoffautomation.com

Nord Gear Corporation

BOOTH #S-2088 (PROMAT)

At Promat 2019, Nord will display new drive technology for conveyor and warehousing systems, increasing productivity and return on investment.

Nord's LogiDrive technology is ideal for intralogistics applications. It provides complete drive solution flexibility; increased energy efficiencies; and reduced variants to improve ROI.

Nord Gear Corporation brings automated drive technologies to Chicago April 8-11, 2019 at Promat – the biggest warehousing, material handling and logistics trade show in North America.

Nord will showcase its integrated and energy efficient drive solutions for manufacturing and material handling to nearly 45,000 supply chain professionals at the event. The intralogistics industry is one of Nord's fastest-growing markets.

According to Torsten Schultz, Nord president, one advantage is the company's global integration. "Three of the world's top five material handling suppliers use Nord drive technology, and we have long-term supply agreements with two of the suppliers."

He added that Nord provides global sales, engineering and customer support. "We support customers and drive systems in 98 countries – wherever their operations are located."

Nord engineers will be at Promat to discuss its complete range of drive solutions for logistics needs at Booth S-2088, including:

The LogiDrive solution delivers integrated drive technologies for manufacturing and warehousing: high efficiency gearboxes; IE4 permanent magnet synchronous motors; and decentralized variable frequency drives (VFDs). In turn, the VFDs and IE4 motors support large speed ranges through gearboxes, to deliver automation for stacker cranes, automated guided vehicles, chain conveyors and roller conveyors, etc. Nord VFDs are capable of operating with all common field bus networks, offer free PLC integration, and provide simple commissioning with plug-in parameter boxes or Nord's free programming software tool, NordCon. Efficient operation at partial load and low speeds make LogiDrive the solution for high-volume warehousing, manufacturing and packaging systems.

Right-angle worm, helical in-line and two-stage helical bevel gear units – Nord's innovative distributed control AC vector drives and motor controllers operate near or directly mounted on motors and reduce load on the higher level control system. Plus, Nord's decentralized VFDs can be freely configured and adapted to hundreds of applications: conveying, lifts, pumps, etc. As result, customers obtain an optimum drive solution and reduce installation and operating costs. **PTE**

For more information:
Nord Gear Corporation
Phone: (608) 849-7300
www.nord.com

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Efficient Layout Process of Cylindrical Gears with Manufacturing Constraints

Ilja Tsikur

Introduction

Cylindrical gear design can be divided into three steps. In the first step, rough gear pair dimensions such as center distance and face width are being estimated. Center distance and face width are directly linked to the available space (housing dimensions) and influence the overall size, weight and cost of the gears. In addition, the torque capacity strongly depends on the chosen gear materials, heat treatment and gear quality. Although case-hardened gears tend to give a higher torque capacity than nitrided gears, a final machining process like for example grinding is required to compensate the hardening distortion. Considering all these factors in a gear rough sizing and finding the best solution becomes a tough challenge.

In the next step, gear macro geometry is defined. In a conventional gear manufacturing process, the choice of normal module, pressure angle and reference profile are directly linked to the cutter geometry. The consideration of available tools in the early design stage can save a lot of effort in the later manufacturing steps. In addition, the resulting gear geometry must satisfy the required safety factors in accordance with the selected gear strength calculation method. Although a higher gear root radius tends to give higher root safeties, it may produce contact interference and require a special cutter. Evaluating different geometric solutions and eliminating non-feasible ones in the early design phase becomes an important task.

In the last phase, gear micro-geometry is defined. The aim of this step is to specify flank line and profile modifications for optimal contact pattern, lower noise emissions and various other parameters. Here, the choice of modification parameters is directly linked to the final machining process. Often a grinding worm with associated dressing wheel is used. If a specific list of grinders/dressers is available, it makes sense to consider them in the layout process to avoid extra costs in the manufacturing process.

In this paper we will present an efficient gear layout procedure based on international standards for gear geometry and strength calculation with the consideration of manufacturing constraints such as lists of hobs, grinders and dressers. The aim is to reduce costs in the later manufacturing steps or alternatively, to be able to predict the need for additional tools in the early design process.

In the Gear Rough Dimensioning section, an approach for gear rough dimensioning is presented. The resulting center distance and face width are used for the next step, i.e. — gear fine-sizing. In Gear Macrogeometry and Optimization, the focus is on gear macro geometry. Parameters such as normal module, pressure angle, helix angle and reference profile are found to meet certain optimization criteria. Two macro-geometric solution examples are used for further analysis; this is followed by Gear MicroGeometry and Optimization. Lead modifications are used to optimize the load distribution along the flank line. Profile modifications and contact analysis are used to optimize the load distribution in profile direction and reduce gear noise. Each chapter also focuses on selected manufacturing constraints that influence the overall design process of cylindrical gears.

Gear Rough Dimensioning

In the first step, gear rough dimensioning is performed. The aim of this step is to find the optimal center distance and face width. These two parameters basically define the overall gearbox dimensions — either for a one-stage or a multi-stage gearbox — and are directly linked to the housing dimensions. The estimation is based on the selected calculation method for gear geometry and strength. The calculation method is defined by the chosen standards (DIN, ISO, AGMA, VDI, GOST, etc.), and the required safety factors; typically for root

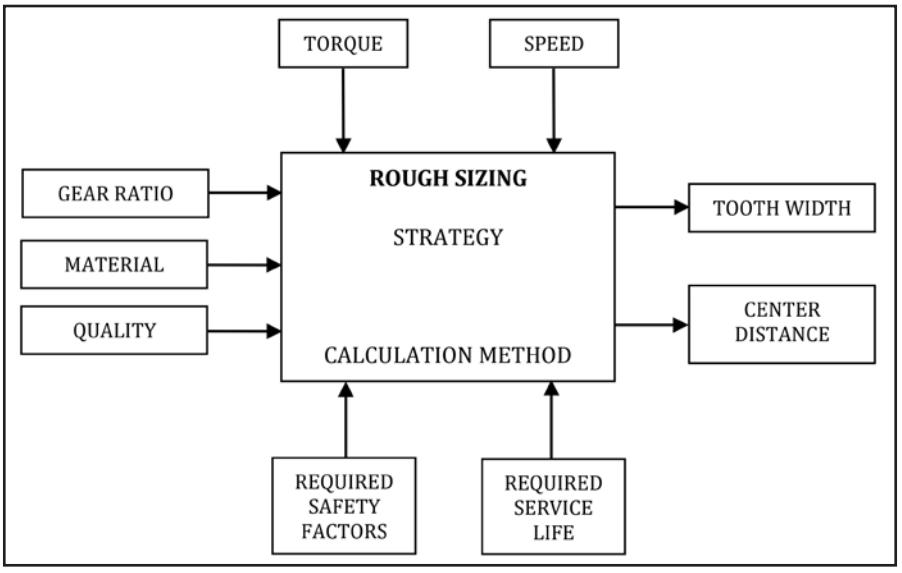

Figure 1 Rough sizing procedure.

This paper was first presented at the 2018 Lyon International Gear Conference.

a [mm]	b_1 [mm]	b_2 [mm]	m_n [mm]	z_1	z_2	i	$SF_{smallest}$	$SH_{smallest}$	P_{max} [kW]	W [kg]	T_{max}/W [Nm/kg]	dB(A)
97.660	60.930	59.440	2.972	16	49	3.063	2.330	1.000	49.952	8.547	37.205	77.413
100.000	61.232	59.482	3.000	16	50	3.125	2.322	1.000	49.970	9.026	35.246	77.997
106.000	49.540	48.040	2.500	21	62	2.952	1.692	1.002	50.176	8.139	39.247	78.171
106.000	50.497	48.997	2.750	19	56	2.947	1.871	1.001	50.059	8.282	38.477	78.382
106.000	50.408	48.908	2.500	21	64	3.048	1.801	1.001	50.069	8.334	38.246	77.533
106.000	51.000	49.500	2.750	19	58	3.053	1.958	1.001	50.107	8.417	37.897	77.659
106.000	52.974	51.474	3.000	17	52	3.059	2.135	0.998	49.786	8.763	36.167	78.341
106.000	52.951	51.451	3.000	17	53	3.118	2.174	0.998	49.790	8.785	36.083	77.960
106.000	54.602	53.102	3.000	17	54	3.176	2.242	1.000	49.962	9.090	34.992	77.691
106.000	55.972	54.472	2.750	18	57	3.167	1.954	0.999	49.944	9.394	33.846	78.568
106.000	55.997	54.497	2.750	19	59	3.105	2.282	0.994	49.445	9.367	33.605	77.251
106.000	61.196	59.696	3.000	16	52	3.250	2.309	0.999	49.894	10.359	30.662	79.068
111.292	43.990	42.920	2.146	25	78	3.120	1.492	1.000	49.987	8.162	38.987	77.012
112.000	42.797	41.484	2.250	25	74	2.960	1.471	0.999	49.925	7.868	40.396	77.661
112.000	43.813	42.500	3.000	19	56	2.947	2.057	0.999	49.945	7.975	39.869	77.469
112.000	44.781	43.468	2.750	20	61	3.050	1.832	1.000	49.998	8.270	38.488	77.761
112.000	45.130	43.817	2.250	24	74	3.083	1.456	0.998	49.827	8.416	37.693	78.094
112.000	45.307	43.994	2.250	24	75	3.125	1.509	0.998	49.805	8.472	37.424	77.783
112.000	46.554	45.241	3.000	18	55	3.056	2.012	1.000	49.969	8.610	36.949	78.304
112.000	46.485	45.172	2.750	20	62	3.100	1.916	0.998	49.794	8.617	36.787	77.521
112.000	47.845	46.532	3.000	18	57	3.167	2.129	1.000	49.955	8.904	35.716	77.668
112.000	48.688	47.375	2.500	23	68	2.957	2.025	0.999	49.903	9.027	35.193	76.962
112.000	48.116	46.803	2.500	21	67	3.190	1.663	0.999	49.946	9.056	35.113	78.253
112.000	48.239	46.926	2.500	21	68	3.238	1.713	0.999	49.946	9.104	34.927	77.924
112.000	49.552	48.239	2.750	19	60	3.158	1.846	0.999	49.932	9.298	34.186	78.712
112.000	52.968	51.655	3.000	17	55	3.235	2.150	0.999	49.899	10.008	31.741	78.996
118.000	41.232	39.919	2.250	25	79	3.160	1.423	0.999	49.928	8.575	37.065	77.918
118.000	41.764	40.451	2.250	25	78	3.120	1.383	0.999	49.400	8.666	36.288	78.256
118.000	41.782	40.469	2.250	25	80	3.200	1.474	0.993	49.330	8.715	36.033	77.669
118.000	44.976	43.663	2.250	24	78	3.250	1.443	0.999	49.881	9.472	33.524	78.792
118.000	45.662	44.349	2.250	25	81	3.240	1.744	1.001	50.105	9.632	33.115	77.328
141.955	28.080	25.920	4.320	16	49	3.063	2.266	1.000	50.009	7.923	40.184	77.413
161.648	20.260	18.700	3.117	25	78	3.120	1.447	1.000	50.014	7.545	42.201	77.012

Figure 2 Rough sizing: a — center distance; b — face width; mn — module; z — number of teeth; i — gear ratio; SF — root safety; SH — flank safety; P — max transmittable power; W — weight, Tmax/W — power density.

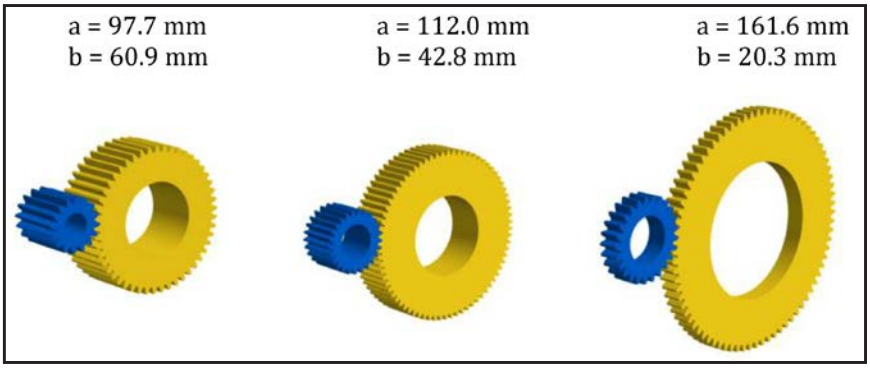

Figure 3 Solution with small center distance vs. high center distance.

and flank, but in some cases also for scuffing, micro-pitting, wear etc.

The main input parameters for rough sizing are torque (or power), speed, required gear ratio, gear material and quality, heat treatment and requested service life (Fig. 1). According to ISO 6336 (Ref. 1) material endurance limits depend on the surface hardness, material quality and heat treatment. Consequently, if the gearbox dimension requirements are not met, a different material, heat treatment or a higher gear quality should be applied.

Once the input data, required safety factors, and the calculation method are fixed, a batch calculation can be performed to extract different geometric solutions. The idea is to search for all feasible solutions in terms of center distance and face width while the safety factors are met and a reasonable quotient between face width and normal module b/mn is maintained (for automotive applications typically b/mn ≈ 6, for industrial gearboxes b/mn ≈ 20). Figure 2 shows an example of such a batch calculation, sorted in terms of center distance. In this early stage, it is possible to estimate the size, weight and power density range of the gearbox variants.

The solution with the smallest center distance results in small gearbox dimensions but is less attractive in terms of weight or power density. The solution with the highest center distance has, in this example, lowest weight and highest power density but is due to upper limits for gearbox size not applicable. The solution in between (a = 112) gives a good trade-off between small gearbox size, low weight and second highest power density.

Figure 3 illustrates two solutions with minimum and maximum center distance. Both solutions are feasible, since the requested safety factors are met. At this point the engineer must make a choice, which solution is optimal for the given application. Different strategies can be applied during the search for an optimum solution.

An often-used approach is to minimize the weight of the gears due to its direct link to manufacturing costs (material price per kg). Figure 2 illustrates the optimization potential for a 50 kw gearbox: the choice of the center distance may save up 25% of gear weight (solutions between 5.4 kg and 7.1 kg). A further approach would be to maximize the power density of the gearing (max. transmittable torque / per kg) — a nice trade-off between low weight and high transmittable power. In some applications e.g. plastic gears, the solutions with minimum center distance (smallest gearbox dimensions) are preferred, due to limited space in the end-product, or with the highest module to reduce the influence of manufacturing tolerances.

Thus, gear rough sizing is an important step in the gear design process. It provides a range of possible gearbox dimensions and allows performing an optimization of gear weight, size and manufacturing costs. In the next step, gear macro geometry needs to be optimized.

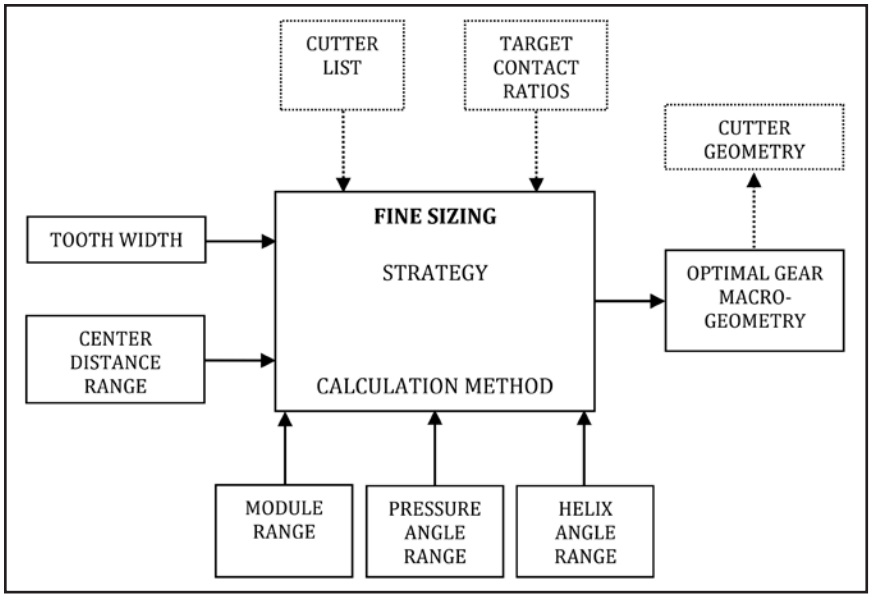

Figure 4 Fine-sizing.

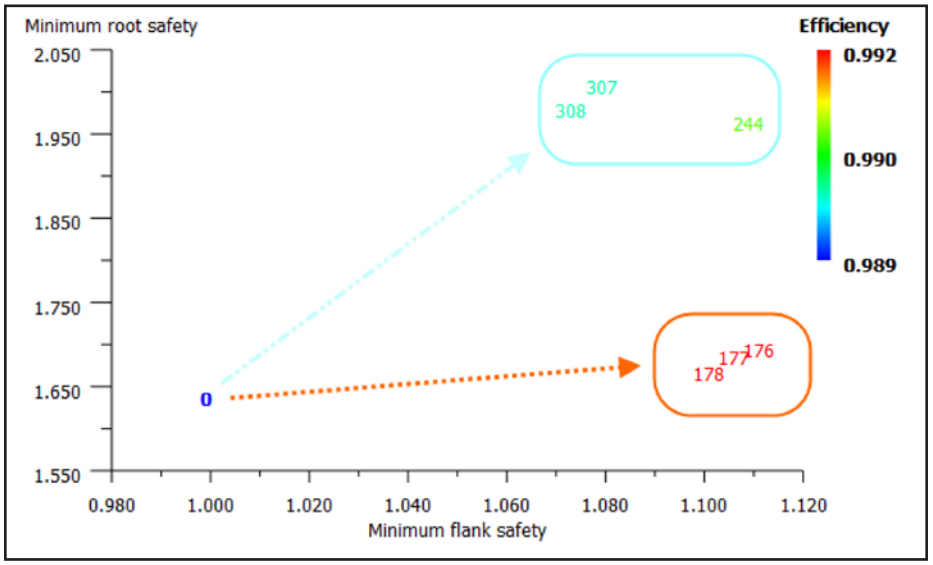

Figure 5 Fine-sizing and analysis in terms of safety.

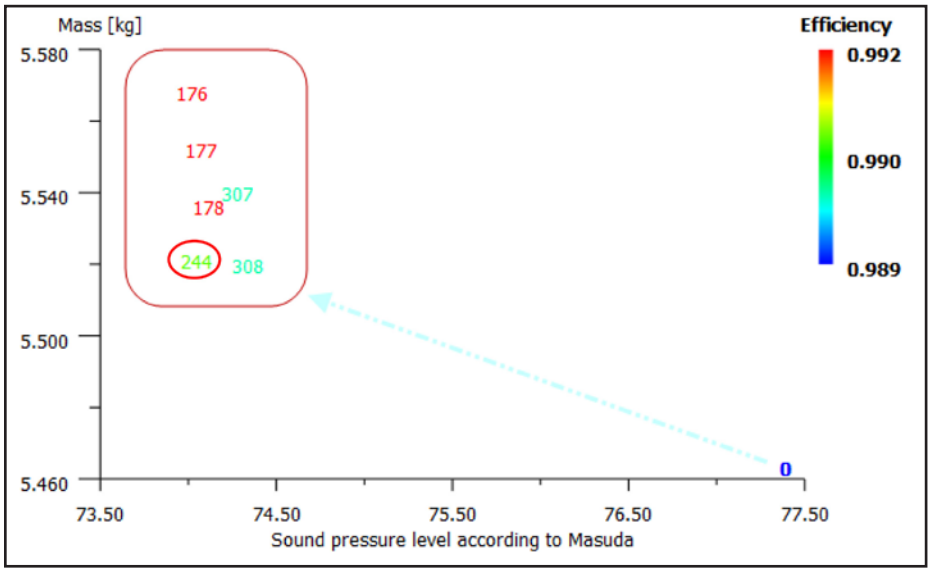

Figure 6 Fine-sizing, analysis in terms of sound pressure level, mass and efficiency.

Gear Macrogeometry and Optimization

Once the center distance and face width are fixed, gear macro geometry can be optimized with the so called fine sizing strategy. The main idea is to perform a variational calculus of gear main parameters, such as normal module, pressure angle, helix angle, number of teeth, profile shift and reference profile (Fig. 4). With modern software tools, such a calculation may easily produce over 1,000 different geometric solutions. The main challenge is to eliminate all non-feasible variants and apply a clever strategy to find an optimum.

For conventional hobbing or pinion type cutting, the choice of normal module, pressure angle and gear reference profile is directly linked to the tool geometry. Thus, manufacturing constraints may limit the number of feasible solutions. Figure 4 shows two possible approaches: a list of available cutters may be used as input to the fine sizing procedure to save costs that may arise due to the need of a special cutter in the later manufacturing process. On the other hand, if the optimized gear design shall be unique, the cutter geometry becomes a result of the calculation and opens new optimization potential. For example, one may define a desired transverse contact ratio (eps_a ≥ 2) and use this constraint to iterate over the gear reference profile to get solutions with high contact and lower variation of the contact stiffness.

While keeping the center distance and face width fixed, one can now iterate over a range of normal module, pressure, and helix angle over different combinations of number of teeth and profile shift coefficients while eliminating solutions:

- where minimum safety factor requirements are not met
- with an undercut
- where tooth thickness at the tip is too small
- where deviation from the requested gear ratio is too large
- where specific sliding (wear, friction) is too high

A simple algorithm can sort and extract best solutions in terms of gear ratio, strength, weight, contact stiffness, specific sliding etc. and provide a list of best overall solutions, based on a weighted combination of the above criteria. Figures 5 and 6 illustrate the final stage of such an optimization, where only several best solution candidates remain. Solution Nr. 0 was the starting point after the rough sizing procedure. All other solutions are the result of the optimization, while maintaining the same center distance and face width (same gearbox dimensions).

All optimized solutions show a significant increase in safety factors, efficiency and a lower sound pressure level according to Masuda (Ref. 5). Solution number 244 shows a good trade-off between high strength and efficiency with low mass and noise level.

Thus, we have introduced one effective method to optimize gear macro-geometry under given manufacturing constraints. In the next step, gear micro-geometry is defined. For further analysis, we will use two different gear variants (Fig. 7) from the fine sizing procedure. The gearing on the left has a standard ISO 53: reference profile C (Ref. 2). The gearing on the right has a deep tooth profile, optimized for a transverse contact ratio of 2 and has a slightly lower normal module. Other parameters like center distance, face width, pressure angle, helix angle and gear ratio remain the same.

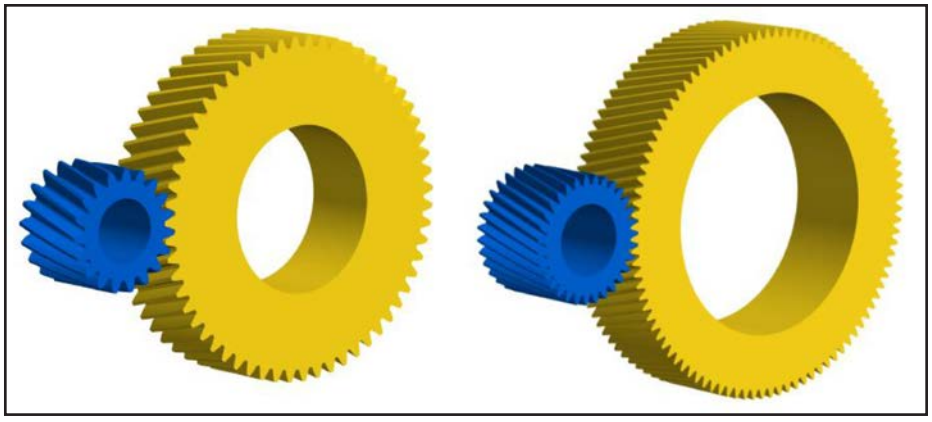

Figure 7 Example of two optimal geometric solutions with standard reference profile (left) and deep tooth profile (right).

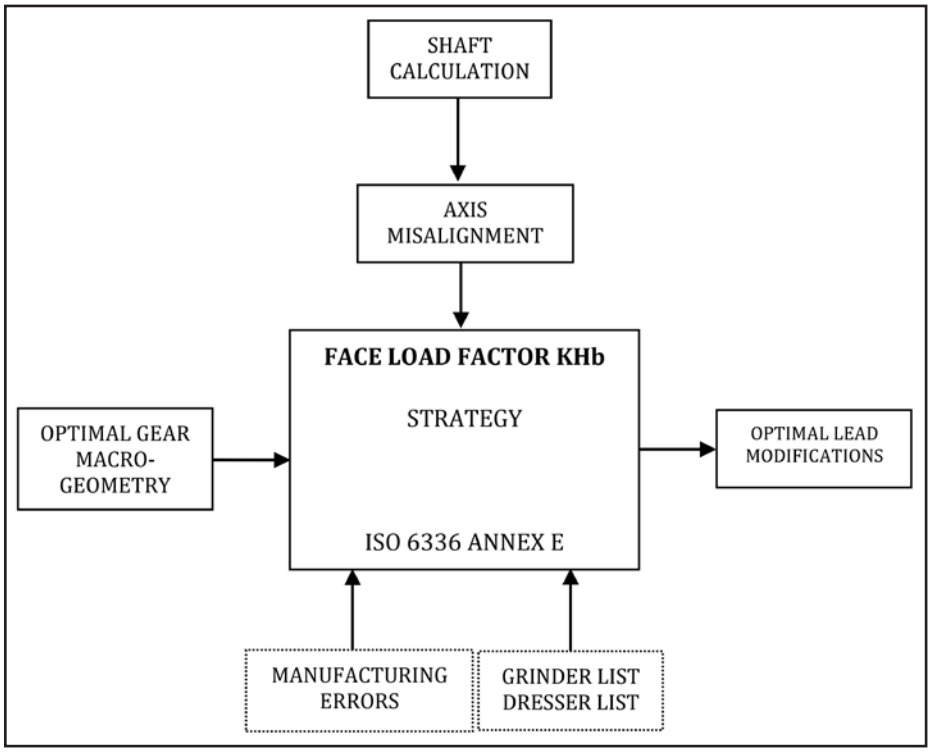

Figure 8 Optimization of face load factor with lead modifications.

Gear Microgeometry and Optimization

In the third and final step, gear microgeometry is defined. First, flankline modifications are applied to compensate shaft bending and torsion, misalignments due to manufacturing errors, bearing clearance, deformation and influence of the housing.

Optimal flankline modifications will normally increase the torque capacity of the gearbox due to a more even load distribution along the flank, thus reducing the face load factor $K_{H\beta}$. Typically, a helix angle modification is applied to compensate shaft misalignments, and a crowning to compensate the random manufacturing errors and torsional effects.

Once the load distribution along the flank is optimal, profile modifications are applied to reduce gear noise. Other effects like lower contact temperature and higher efficiency, smooth normal force distribution or higher micropitting resistance may be achieved. However, in this paper we will focus on the optimization of noise related parameters such as the contact path under load, peak-to-peak transmission error, force excitation and harmonics.

Flankline (lead) modifications. The face load factor $K_{H\beta}$ is defined as the ratio between the highest line load divided by the average load over the face width (Ref. 1). Thus, under optimal conditions the face load factor would be equal to one. ISO 6336 Annex E describes one possible approach to calculate the face load factor $K_{H\beta}$, while considering shaft misalignment due to bending, torsional deformation and manufacturing errors (Fig. 8). Flankline modifications are applied to compensate the uneven load distribution.

For gears with higher quality, the face load factor mainly depends on the shaft deformation due to bending. It is thus important to perform a shaft deformation calculation when optimizing the load distribution. Figure 9 illustrates the results of an analytical calculation of shaft deformation with consideration of non-linear bearing stiffness resulting from bearing inner geometry,

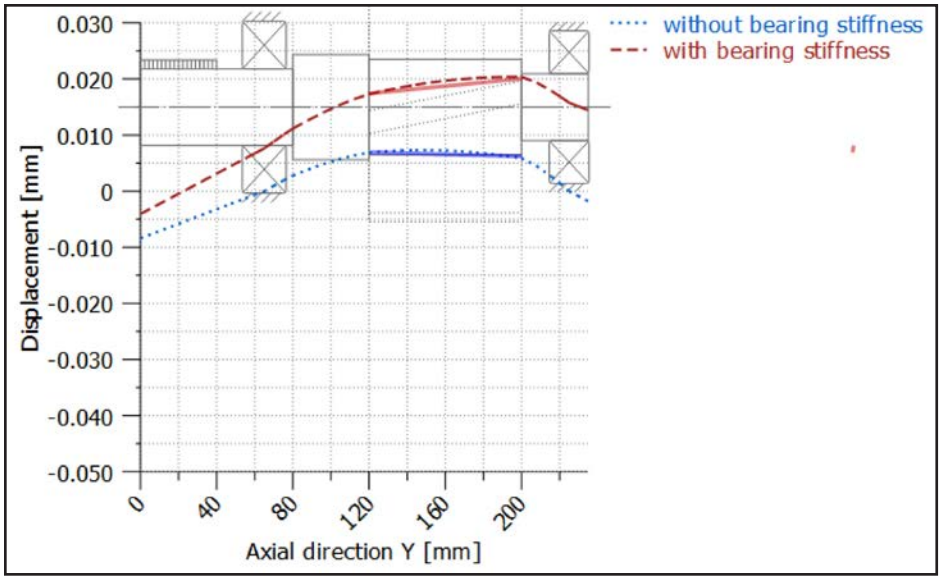

Figure 9 Shaft bending line.

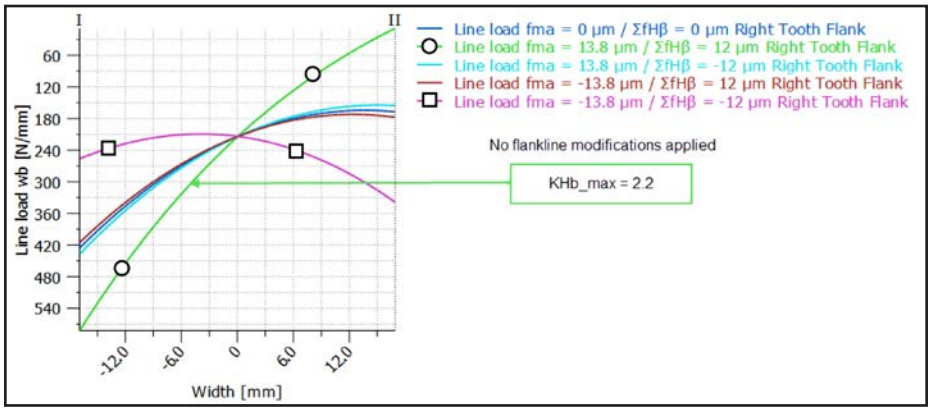

Figure 10 Resulting line load without flankline modifications.

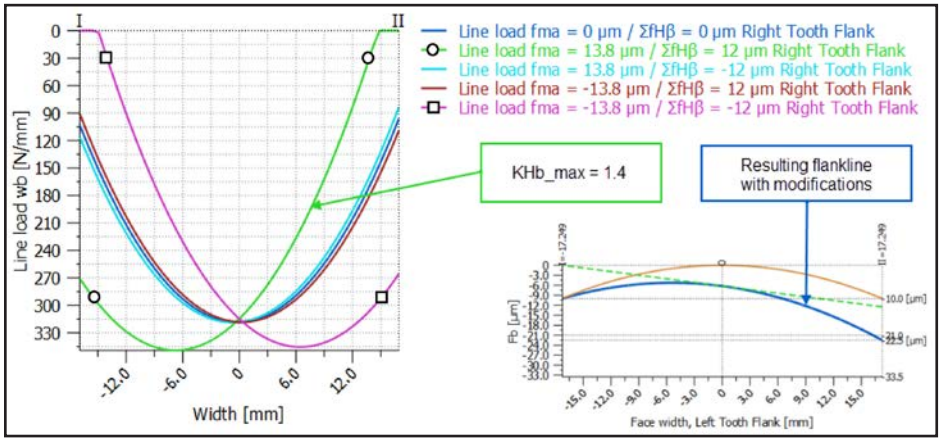

Figure 11 Resulting line load with flankline modifications.

as described in ISO/TS 16281 (Ref. 3) (see red curve). The blue curve illustrates the bending line with infinite bearing stiffness. Thus, if bearing stiffness is not considered, the sizing of a helix angle modification can be wrong and, in some cases, even provide worse load distribution than if no modification applied at all.

In addition, manufacturing allowances like axis non-parallelism (f_{ma}) and helix slope deviation ($f_{H\beta}$) should be considered. Since manufacturing errors can either have a positive or a negative sign, several scenarios must be analyzed. Figure 10 illustrates the load distribution for 5 different cases:

- f_{ma} = 0 and $f_{H\beta}$ = 0
- f_{ma} (+) and $f_{H\beta}$ (+)
- f_{ma} (+) and $f_{H\beta}$ (-)
- f_{ma} (-) and $f_{H\beta}$ (+)
- f_{ma} (-) and $f_{H\beta}$ (-)

According to ISO 6336, Annex E, the strength calculation has to be performed with the highest face load factor (in this example, $K_{H\beta}$ = 2.2) that results from the above 5 cases.

To optimize the load distribution and the face load factor with manufacturing errors, an additional crowning is typically applied. The idea is to reduce the maximum line load and for all scenarios of manufacturing errors and shift the peak line load away from the gear edges. Figure 11 illustrates the line load with an additional crowning of 10 microns. In this example, the highest face load factor appears for f_{ma} (+) and $f_{H\beta}$ (+) and equals around 1.4. Applying the resulting face load factor in the strength calculation resulted in 45% higher root safety and 20% higher flank safety.

One important manufacturing constraint to consider here is the manufacturing twist. When using generation grinding to produce crowning in helical gears, a twist may appear due to the grinding motion of the tool. If not compensated, this may lead to a higher effective line load. Figure 12 illustrates the shape of the crowning with the influence of the twist due to manufacturing. The compensation of the twist is not a simple task — especially due to the lack of available literature — and requires the use of modern grinding machines.

Loaded tooth contact analysis. The aim of loaded tooth contact analysis (LTCA) is to evaluate the gear mesh under load. For the calculation of tooth deformation, a tooth stiffness model is required. An analytical model for tooth deformation was presented by Weber and Banaschek (Ref. 6), where gear deformation is divided into three main components:

- Gear body deformation
- Tooth bending deformation
- Hertzian flattening

Based on this theory, an analytical stiffness model can be created. A loaded tooth contact analysis can then be performed based on the tooth deformation, shaft misalignments, manufacturing errors (e.g. pitch error), and a defined partial load for the calculation (Fig. 13). The results of LTCA provide important parameters for noise characterization and optimization:

- Transmission error
- Amplitude spectrum of the transmission error
- Force excitation
- Path of contact under load

The transmission error (TE) describes the deviation of the theoretical contact point from the point of contact under consideration of tooth deformation. Especially the peak-to-peak transmission error (PPTE) is a valuable parameter for noise optimization. The Fourier transformation provides the orders of harmonics and allows evaluation of the excitation frequencies. From the transmission error and contact stiffness, it is possible to derive the excitation force (EF) (Ref. 7) that allows comparison of different geometric solutions in terms of vibration excitation and — along with the transmission error — to find the best variant with reduced gear noise. Furthermore, the path of contact under load shows the change of pressure angle at the beginning and end of the meshing. This phenomenon will later be referred to as "contact shock" (Fig. 14).

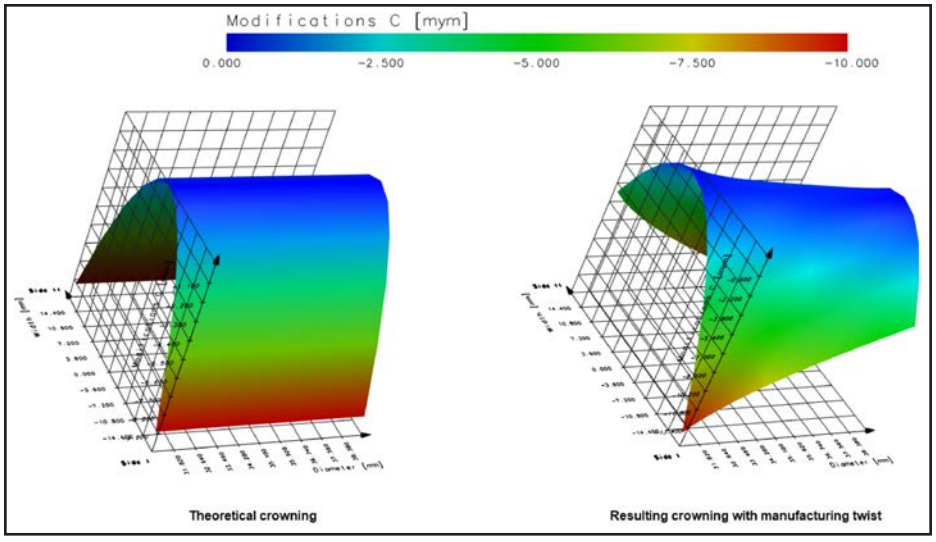

Figure 12 Influence of manufacturing twist on crowning.

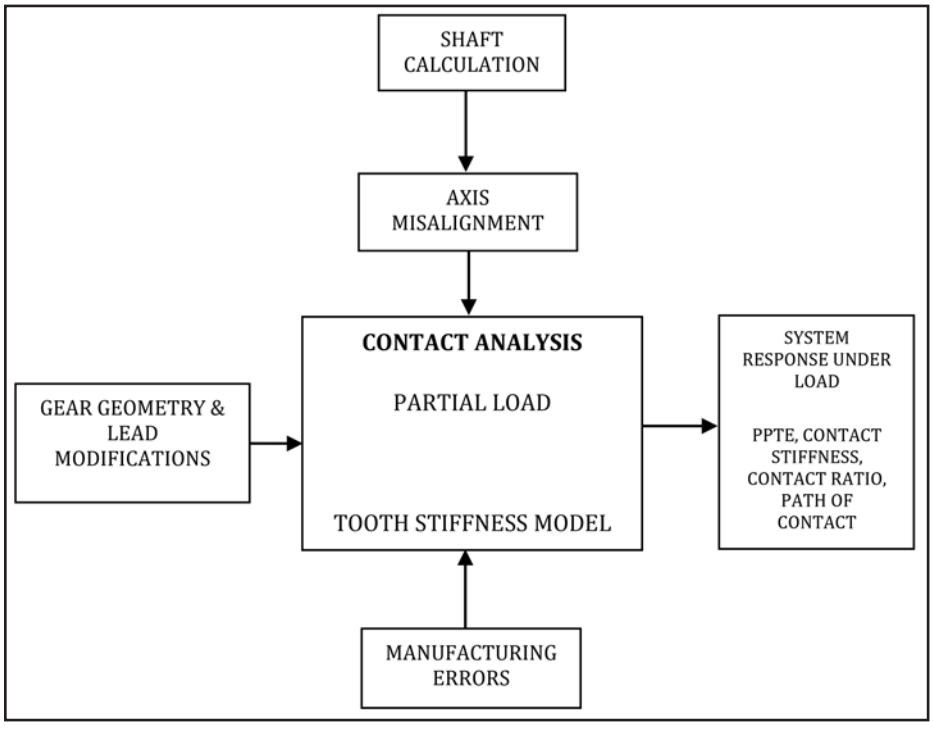

Figure 13 Contact analysis.

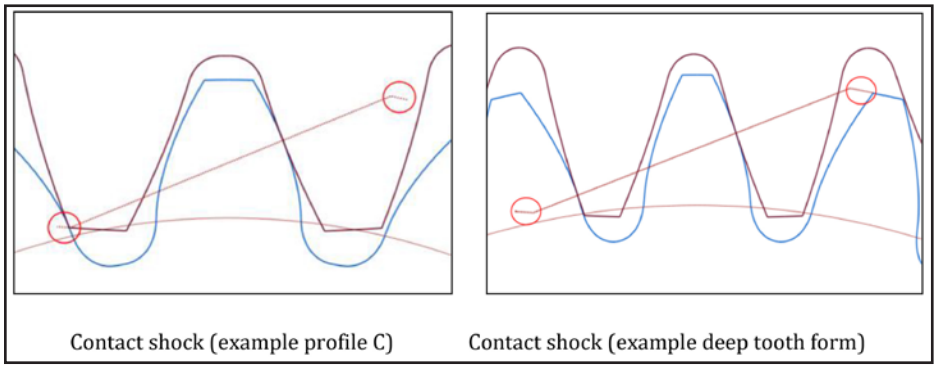

Figure 14 Contact shock.

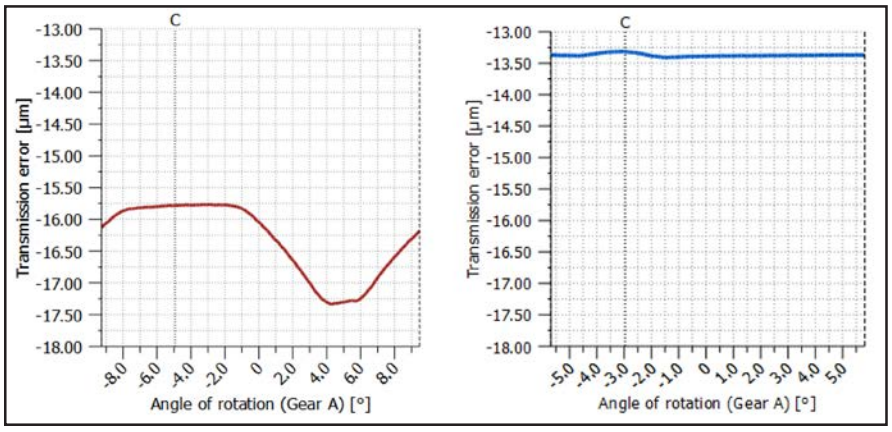

Figure 15 Transmission error.

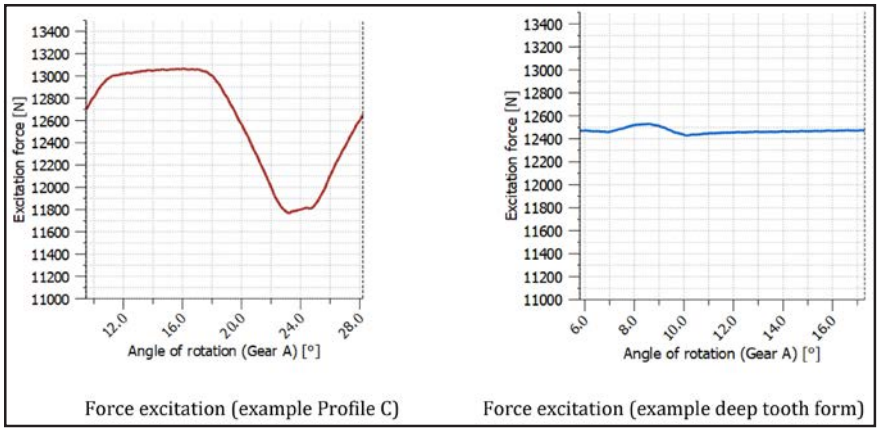

Figure 16 Excitation force.

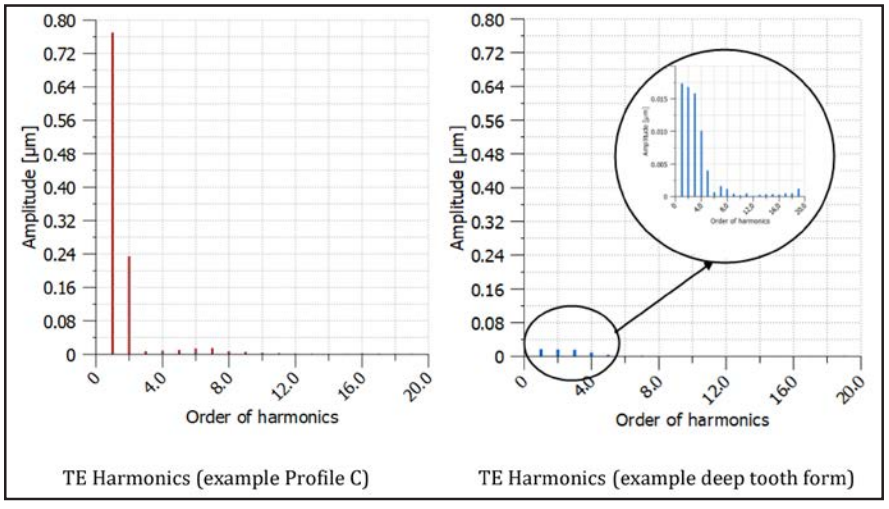

Figure 17 Amplitude spectrum.

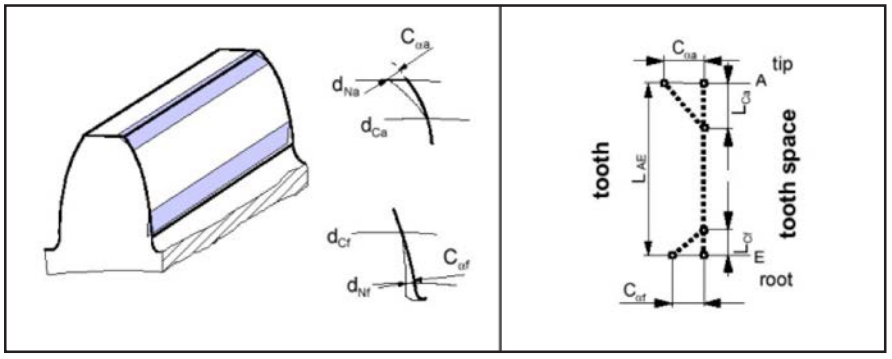

Figure 18 Tip and root relief.

In the previous Gear Macrogeometry and Optimization section, two example solutions from the fine-sizing procedure were presented. Figure 17 illustrates the results of a loaded tooth contact analysis. Both solutions show a contact shock in the beginning and at the end of the mesh. Due to a higher contact ratio and a higher stiffness, the amplitudes of transmission error and force excitation are lower for the solution with a deep tooth form. On the other hand, the amplitude spectrum shows less significant order of harmonics for the standard reference profile.

Profile modifications. The final step is the sizing of profile modifications. Different features such as noise, contact temperature, efficiency, micro-pitting or scuffing can be improved with well sized profile modifications. In this paper we will focus on the reduction of noise with following a simple strategy:

1. Eliminate contact shocks at the beginning and at the end of the mesh.
2. Reduce the amplitude of the transmission error (PPTE).
3. Reduce the second and higher order of harmonics to become as close as possible to zero.

In the ISO 21771 different modification types are defined. Typically, a tip relief (Fig. 18) on both gears is applied to reduce gear noise. The amount of tip relief *Caa* is adjusted to eliminate contact shocks and the tip relief roll length *Lca* is chosen to minimize PPTE.

Figure 19 illustrates the path of contact under load with eliminated contact shocks when applying a tip relief of $C\alpha a = 22\,\mu m$ in the example with a standard reference profile and $C\alpha a = 15\,\mu m$ for the deep tooth form example.

The peak-to-peak transmission error (Fig. 20) was reduced in both cases. The lowest noise levels can be expected for the example with the deep tooth form: the transmission error curve is smoother and has a lower amplitude. This can be explained with the higher contact ratio and the nearly constant stiffness of the deep tooth form. Same effects can be observed for the excitation force (Fig. 21). Although the average value of the excitation force did not change for both variants, the amplitude levels are decreased. Figure 22 illustrates another advantage when applying a tip relief, i.e. — the second and higher order of harmonics were reduced, especially for the example with the deep tooth form. The shape of a signal with only one dominant harmonic is similar to a sine/cosine wave. On the contrary, if many orders of harmonics are dominant, the signal has rather the shape of a square function, which is unfavorable.

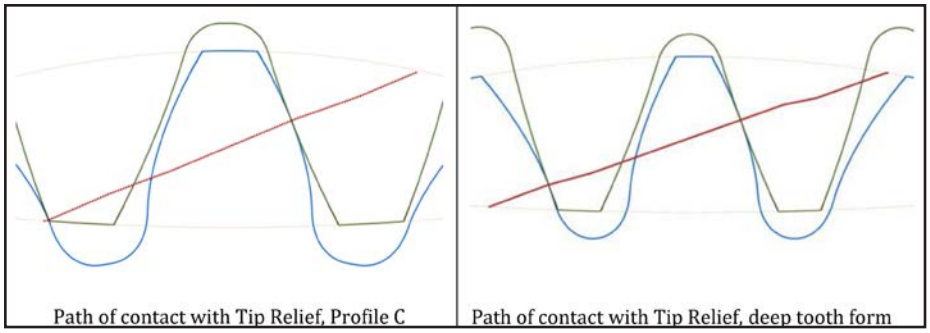

Figure 19 Optimized contact path.

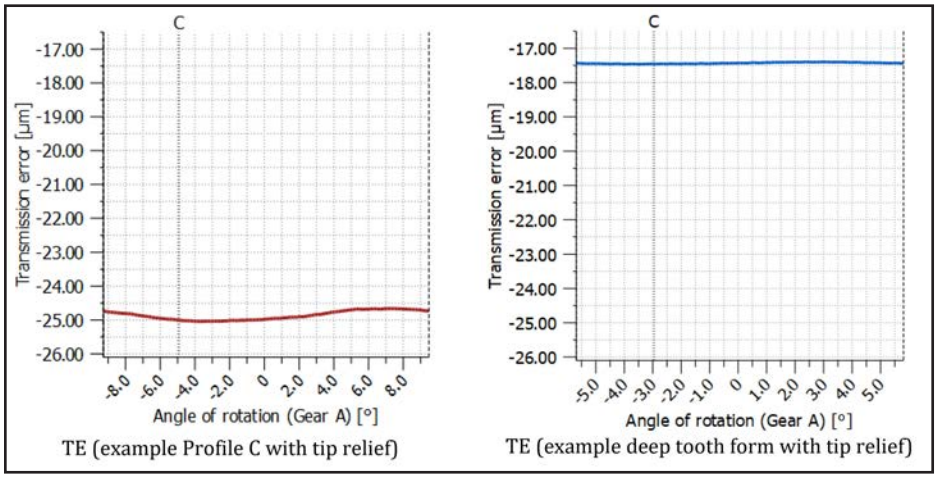

Figure 20 Optimized transmission error.

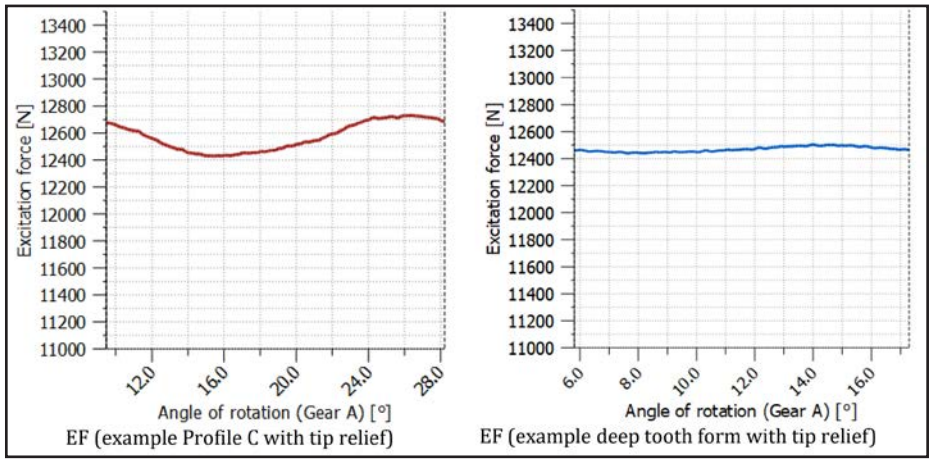

Figure 21 Optimized force excitation.

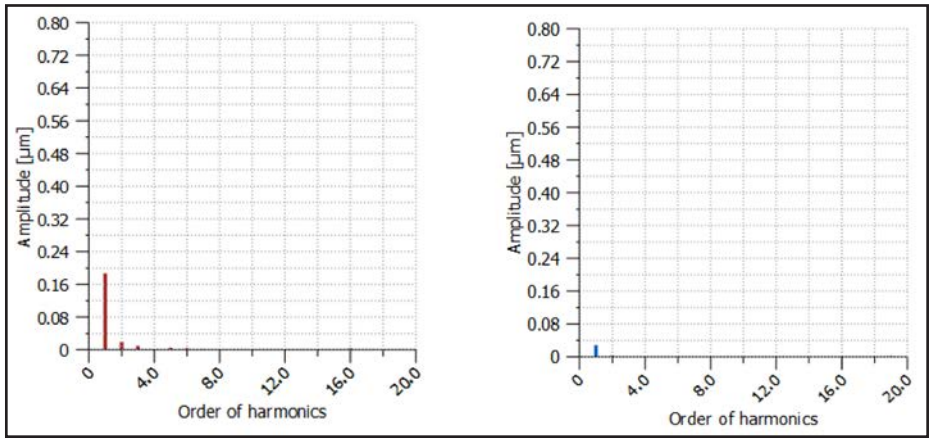

Figure 22 Optimized amplitude spectrum.

Figure 23 illustrates the profile diagrams of both variants. If manufactured with generation grinding, a dressing wheel is typically used to trim the grinding worm that later produces the modifications. The evaluation, if a specific modification can be carried out with available grinders/dresses can save costs and time. In some cases, modifications are directly integrated into the shape of the hobbing cutter.

Gears are usually manufactured with a grinding stock that will be removed in the grinding process to meet dimensional requirements. The choice of the gear heat treatment method basically defines the amount of grinding stock for the finishing process (Ref. 8). By selecting a heat treatment processes with smaller distortion, the amount of grind stock can be reduced to minimize machining of hardened surfaces and reduce the overall costs of manufacturing. By this, the manufacturing of modifications is linked to the heat treatment/finishing process and should be considered in the design process.

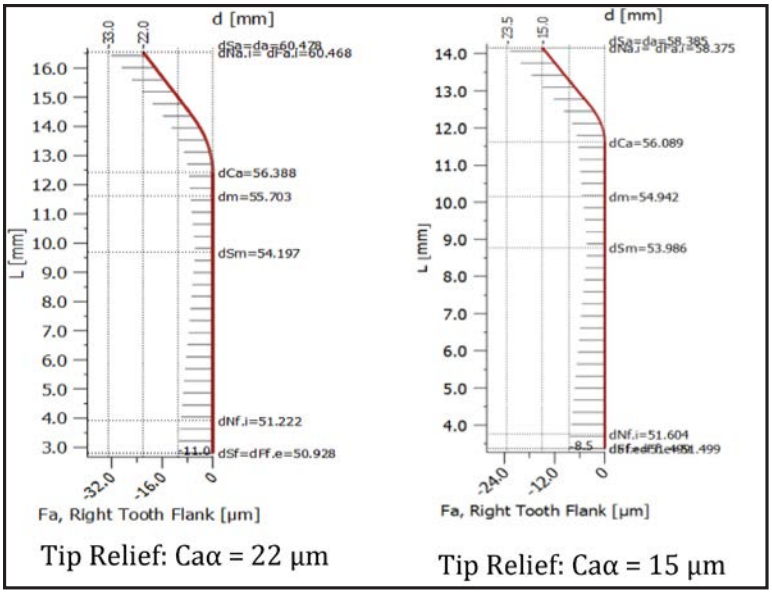

Figure 23 Profile diagrams, Profile C (left), deep tooth form (right).

Summary

The layout procedure of cylindrical gears can be divided into three main steps: rough sizing, fine sizing and modification sizing. In the rough sizing step gearbox dimensions like center distance and face width are defined. If the resulting gearbox dimensions are too large, a choice of a better material or heat treatment process can help.

In the next step, gear macro-geometry is defined. Parameters such as normal module, pressure angle, helix angle and reference profile are optimized to meet different design criteria. A list of available cutters can help to optimize the manufacturing costs. Alternatively, a non-standard reference profile can be used to achieve certain properties like, for example, a higher mesh stiffness or contact ratio.

In the final step, gear micro-geometry is defined. It is shown that applying well-designed flank line modifications can significantly increase the torque capacity of a gearbox. A manufacturing twist resulting from the manufacturing process may limit the optimization potential. A loaded tooth contact analysis allows quantification of noise parameters such as contact path under load, including contact shocks, peak-to-peak transmission error, force excitation and harmonics. Profile modifications are then applied to improve the above parameters and decrease the source of vibrations. **PTE**

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For more information.

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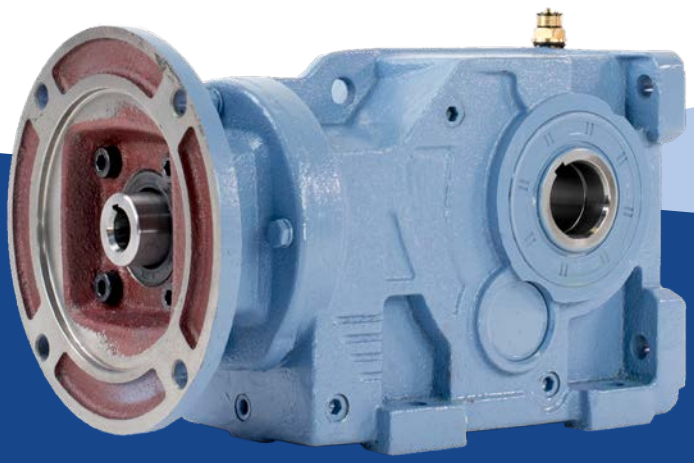

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Optimization of Power Density by Local Gear Failure Modeling

Marco Kampka, Christian Brecher and Christoph Löpenhaus

Introduction and Motivation

Power density is a key factor in gear design. Increasing the power density enables engineers to use smaller gears for their applications which lead to smaller and lighter gear boxes. The benefit for example for the automotive industry is less moving load in the vehicles and therefor a reduction of fuel consumption and subsequently a reduction of CO_2 emission. The limiting factor for the increase in power density of gears is the material strength in regard to the critical failure mode.

The most common way to design gears is using industry standards in which the material strength can be obtained either from fatigue limit tables, which are based on test rig results, or from the calculation of local material data (e.g. based on hardness, residual stress, and oxidation) by means of empirical formulae. Due to the limited empirical data, a lot of averaging and approximations are used to make the available standards applicable to a wide range of applications. To cover for the uncertainties due to this fact, the gears will be designed on the safe side and a near maximum power density will not be achieved.

To design the gear closer to the power density limit, a high level of information concerning the load carrying capacity for the specific failure mode is necessary. In this paper, the three major gear failure modes pitting, tooth root breakage and flank fracture will be discussed. Those failure modes have in common that they start with a local exceeding of the material strength in regard to their specific load situation. This paper will show how local FEA-based calculation approaches can be used to design gears closer to their power density limits for pitting, tooth root breakage and flank fracture. The calculation results will be validated in running tests on different test rigs. The testing results will then be compared to the results of the local FEA-based calculation approaches as well as to the common industry standard ISO 6336.

Increasing the power density of gears is always a major goal in gear design. Transmitting higher power with smaller gears decreases the size of the gearbox itself and gives more room for other devices or components. At the same time, the downsizing reduces weight. In an automotive transmission this will lead to a higher fuel efficiency and less CO_2 emission. The required high power density of the gearbox demands an exact calculation method for the strength against the predominant failure modes of the given gear sets. This includes pitting, tooth root breakage and flank fracture. The precise recalculation of the tooth strength is necessary, as the downsizing leads to a reduction of the remaining safety reserves.

With regards to the calculation of the strength of cylindrical gears, a trend towards local calculation approaches is visible. Instead of calculations solely based on standards and global calculation approaches, local approaches based on finite element analysis (FEA) are used. A big advantage of FEA and FE-based tooth contact analysis (FE-TCA), respectively, is the consideration of the exact geometry including flank modifications, the local stiffness behavior, and thus, the precise calculation of forces and stresses. In contrast, global approaches are based on simplified models and phenomenological formulas (Fig. 1).

In the end, the capabilities of both standard calculations and FE methods are limited. The applicability of standards for gears similar to the test data base is very good. Arbitrary gear size, gear geometry, material properties or surface properties may cause issues. For example, larger gears require higher safety factors, whereas smaller gears demand lower safety factors for a correct prediction of strength (Refs. 1–2).

FE methods, however, are also limited with regards to the prediction of the load carrying capacity of gears. Reasons are the dependency of the results upon the

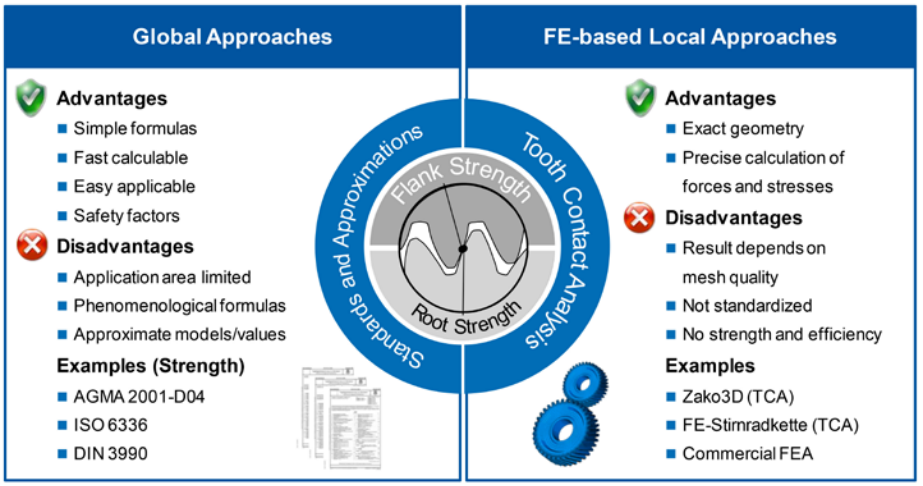

Figure 1 Calculative approaches for flank strength.

mesh characteristics, e.g. — density and uniformity, and missing or simplifying local models and properties, e.g. — friction coefficients and material parameters. Though the loads and stresses can be calculated very precisely, especially considering flank modifications, the prediction of strength is not a common result of today's FE-TCA.

Objective and Approach

The main failure modes of gears are pitting, tooth root breakage and flank fracture. During the design stage existing (ISO 6336-2, 6336-3, AGMA 2001) and proposed (ISO/DTS 6336-4) standards can be used to check designs regarding those failure modes (Refs. 3–6). Since those standards use simplified approaches to calculate the loads and compare them to empirical strength data and due to the nature of standards using conservative estimates, the load carrying capacity limits of the components are most likely not reached. Therefore, potential to increase power density will not be used fully.

One alternative is to use FE approaches. While the composition of stresses and the location of failure initiation are very different, the fatigue failure modes pitting, tooth root breakage and flank fracture have in common that they are all initiated by a local exceeding of the material strength. The material in general is not ideally homogeneous. Each material will, to a certain degree, consist of imperfections that include pores or inclusions. Those imperfections will cause premature failure by crack initiation due to a local stress maximum because of the variation of Young's modulus. This is taken into account by local strength calculation approaches using weakest link models (Fig. 2). During the FE-simulation a probability of failure/survival is calculated for each volume element. The multiplication of the single probabilities will result in the total probability of the calculated failure for the whole component.

This paper will introduce FE-based local calculation methods to predict the failure modes pitting, tooth root breakage and flank fracture. For each failure mode, the special adaption of the calculation methods will be demonstrated. Subsequently, the results of the FE-based methods will be validated by test bench trials and compared to the ISO 6336 standard.

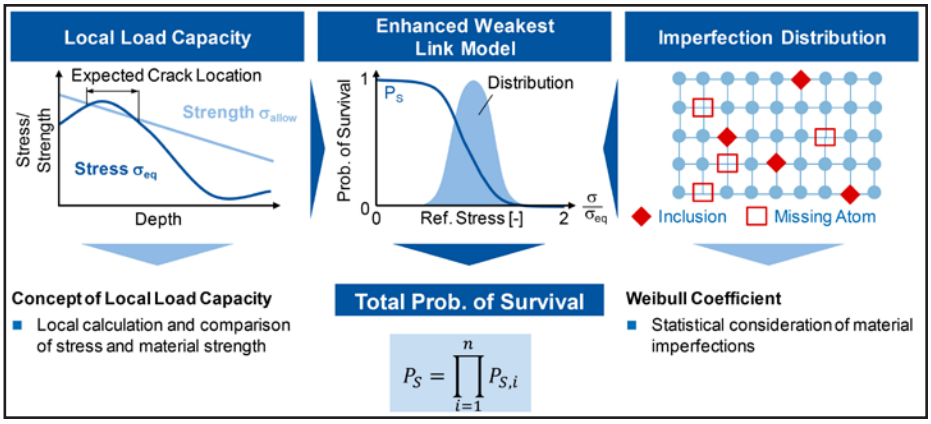

Figure 2 Calculation approach in enhanced weakest link model.

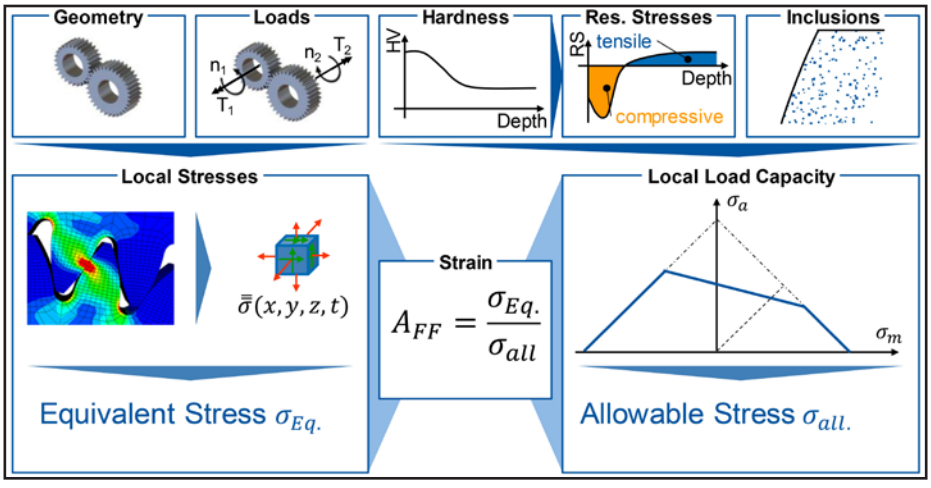

Figure 3 Local strength calculation approach.

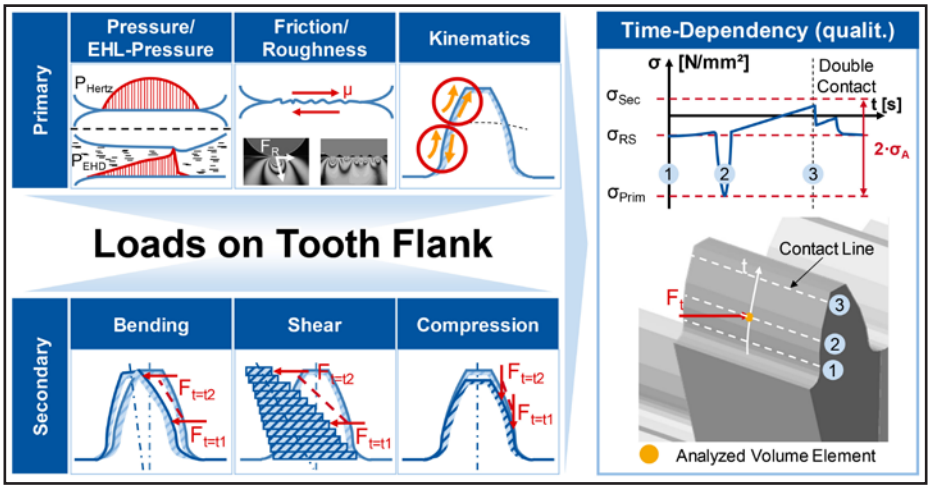

Figure 4 Time-dependency of tooth flank stresses (Ref. 7).

Local Gear Failure Models

The basic input data needed to use a FE-TCA, regardless of the failure mode, is listed in the upper half of Figure 3. To calculate the local stresses the geometry of the gears and knowledge of the loads and kinematics is needed. The time-dependent stress calculation is carried out by means of FEA. The resulting stresses out of the FEA are then combined to an equivalent stress using different stress hypotheses depending on the fatigue failure mode. Those locally calculated equivalent stresses will be compared to the local load capacity of the stressed

element. The local load capacity is derived from the hardness and residual stress profile, the chosen material model and the characterization of the material imperfections in form of inclusions. If the local equivalent stress succeeds the allowable stress, failure will occur.

Pitting. The torque transmission by gears is characterized by locally variable contact conditions on the tooth flank. Therefore, for each contact point the local loads have to be calculated. Direct results of FE-TCA are the local normal forces F_N, the sliding velocities v_g and the normal force asymmetry factor λ (kinematics). The stress cycle that an element on the tooth flank is exposed to during the contact can be divided into two different phases: primary and secondary loads (Fig. 4).

In the non-loaded conditions the residual stresses determine the entire state of stress (point 1). The initially applied primary loads result from the contact flattening due to the Hertzian contact and are characterized by a compressive state of stress that superimposes the residual stresses (Ref. 2). During the contact cycle the loads are characterized by normal, tangential and temperature stresses. After completing the load cycle, the considered volume element is exposed to an increasing tensile stress due to the deformation of the tooth. This part of the load sequence is called secondary load (Ref. 3). The secondary loads are determined by the amount of tangential and radial forces leading to bending, shear and compression states of stresses. The consideration of primary and secondary stresses can lead to an alternating stress state over the entire contact of a tooth pair. The resulting stress amplitudes are higher than just for the Hertzian contact and need to be considered in a strength model.

Besides the consideration of the exact stress state, the material strength has to be taken into account. For the calculation method, measured micro hardness and residual stress profiles are required. The material strength is described according to the conditions in Goodman's diagram that shows the permissible stress amplitude over the acting mean stress (Fig. 5). The approach is applied locally at each element.

The permissible stress amplitude is limited by the compressive/tensile yield strength $R'_{p0.2}$ on the one hand. On the other hand, the endurance strength is described over a huge interval of stress ratios R by Goodman's straight. The level and gradient of the straight depends on the residual stress-free cyclic yield strength σ_{W0} and the mean stress sensitivity M. Accordingly, compressive residual stresses that act as superimposed mean stresses lead to an increased permissible stress amplitude if the yield strength is not exceeded.

The used material model is fully adopted from Hertter (Ref. 8) despite the shown modifications (Fig. 5):

- Mean stress sensitivity is calculated acc. to LIU [9].
- Effective mean stress considers mean stress due to applied load in addition to mean stress due to residual stresses.
- Introduction of Weibull parameter for weakest link model.

The concept for the pitting strength calculation is shown (Fig. 6). The input data for the model consists of the contact geometry, external forces/torques and the material parameters. On this basis the probability of survival of the surface zone and the influenced bulk material is calculated. Based on the input data, a simplified analysis of the contact conditions takes place first. Therefore, the minimum relative film thickness in the contact is calculated. If a sufficient separation of surfaces is given ($\lambda = h_{0,th} / R_{q,mean} > 2$) only the stresses in the volume are evaluated. Otherwise, a micro contact calculation is run in order to consider the stress peaks due to the contact of technical surfaces.

For the time-dependency of stresses (Fig. 4) the state of stress at each volume element is recorded over the entire mesh. Afterwards, the state of stress is compared locally to the material

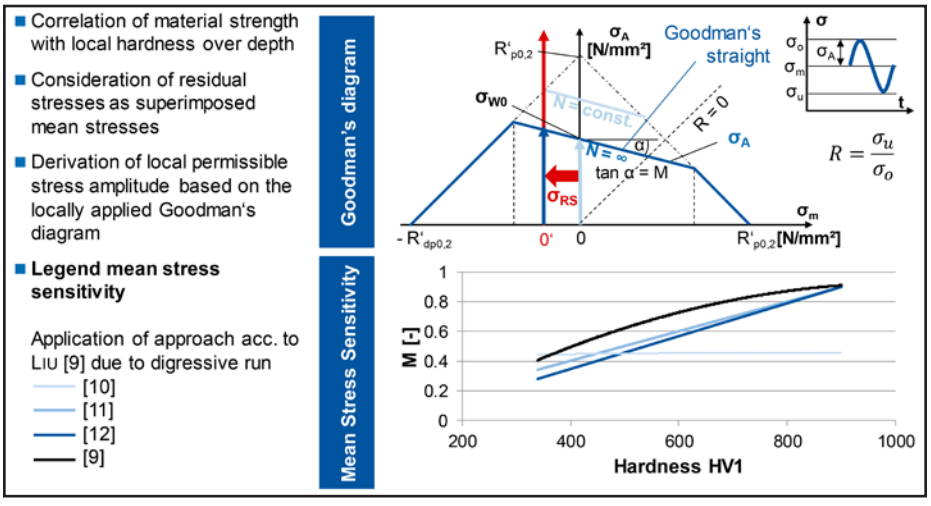

Figure 5 Material strength in tooth flanks (Ref. 13).

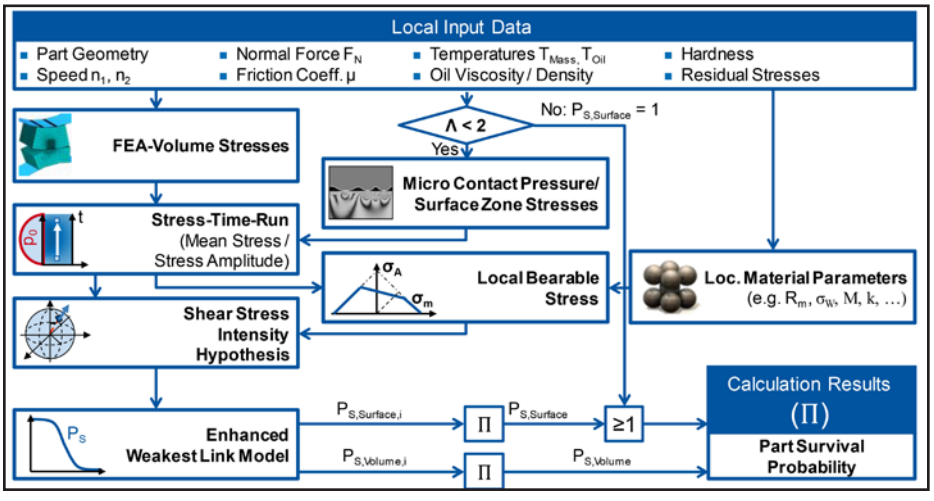

Figure 6 Procedure for local pitting strength calculation (Ref. 7).

strength (Fig. 5). Therefore, the shear stress intensity hypothesis (SIH) acc. to Liu (Ref. 9) and modified by Hertter (Ref. 8) is used. The input parameters are now further enhanced by the mean stresses due to load, as well as residual stresses (Ref. 7). Therefore, the strains A at each cross-section of a volume element are considered over the mesh in an integrative approach (Eqs. 1 and 2).

$$A(\gamma,\varphi)=\sqrt{\frac{a\cdot\tau_{\gamma\varphi,a}^{2}(1+\mathrm{m}\cdot\tau_{\gamma\varphi,m}^{2})+b\sigma_{\gamma\varphi,a}^{2}}{\sigma_{A}}} \quad (1)$$

$$A_{\mathrm{int},A}=\left\{\frac{15}{8\pi}\int_{\gamma=0}^{\pi}\int_{\varphi=0}^{2\pi}[A(\gamma,\varphi)]^{2}\cdot\sin\gamma\cdot d\varphi d\gamma\right\}^{\frac{1}{2}} \quad (2)$$

$A(\gamma,\varphi)$	[-]	Strain of plane (γ,φ)
$\tau\gamma\varphi,m$	[MPa]	Shear mean stress, plane (γ,φ)
σ_A	[MPa]	Permissible Stress Amplitude
$A_{int,A}$	[MPa]	Entire strain of volume element
$\tau_{\gamma\varphi,a}$	[MPa]	Shear stress amplitude, plane (γ,φ)
$\sigma\gamma\varphi,a$	[MPa]	Normal stress amplitude, plane(γ,φ)
a,b,m,n	[div.]	Material Constants

Finally, the probability of survival for each volume element at the surface and in the bulk volume is calculated according to the enhanced weakest link model that is applied on tooth flank contacts (Refs. 7 and 14). To parameterize the weakest link model, the local strain and local Weibull parameters are used. The total probability of survival of the component (final calculation result) is given by the product of all single probabilities of survival. This allows for the rating of an entire component with a single value by combining numerous local results (Eqs. 3 and 4).

$$P_{S,i}=2^{-\frac{1}{V_0}\cdot\int_V A_i^{k_i}dV} \quad (3)$$

$$P_S=\prod_{i=1}^{n}P_{S,i} \quad (4)$$

$P_{S,i}$	[-]	Probability of survival element i
A_i	[-]	Entire strain of element i
P_S	[-]	Probability of survival tooth flank
V_0	[mm³]	Unity Volume
k_i	[-]	Weibull's parameter element i

In order to understand the general relations of influences and stresses in rolling-sliding contacts of gears, the contact conditions of simpler disk-on-disk-contacts have been analyzed first. The simulation of thermo-mechanic loads in the disk-on-disk-contact is done via FEA (Abaqus/CAE) (Ref. 7). In order to reduce the size of the FEA model, the test and counter shaft are represented by segments only (Fig. 7). For a further reduction of calculation time, the mesh density is locally increased in the contact area. The element type is C3D8T with a linear interpolative approach allowing fast calculation. The required mesh density in the contact area was evaluated by comparing the results of a convergence study of Hertzian pressure and with the ideal Hertzian contact theory. The maximum allowable element length found was $l_{FEA}=250\,\mu m$. For temperature stresses at the very surface, the maximum allowable element length was $l_{FEA,T}=50\,\mu m$.

The FEA model allows the consideration of the most important influences on the stresses in the volume of the material due to normal, tangential, and thermal strains of the rolling-sliding contact under load. The values for geometry, normal forces, friction coefficient, and tangential velocities of test and counter shaft were derived from experimental measurements. As the wear of the contacting test parts changes the surface geometry and, consequently, the stress conditions in the subsurface region, a variable surface geometry has to be considered by a spline function. This was possible due to the fine mesh in the contact area.

The procedure for measurement-based surface stress field calculation is divided into three steps (Fig. 8). In a first step, measurement data is imported and modified for subsequent calculations.

Secondly, the pressure distribution under consideration of the technical surface geometry is calculated making

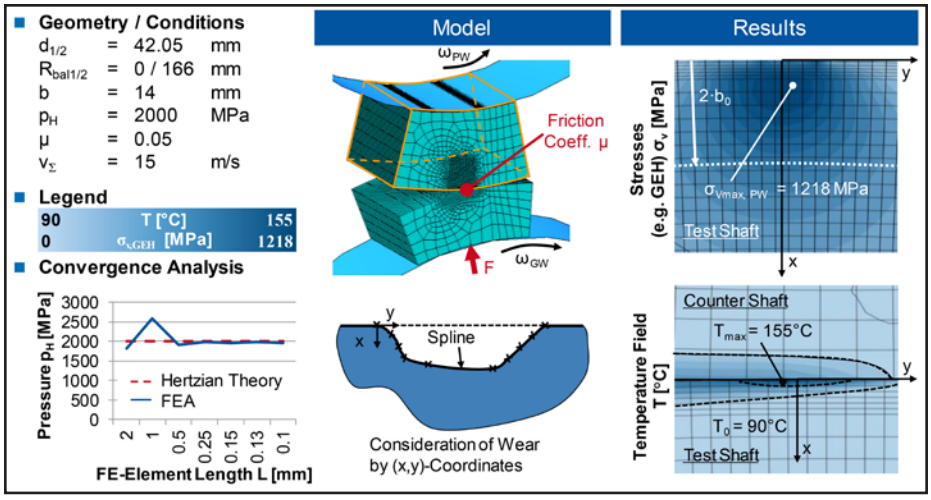

Figure 7 Subsurface stress model (Ref. 7).

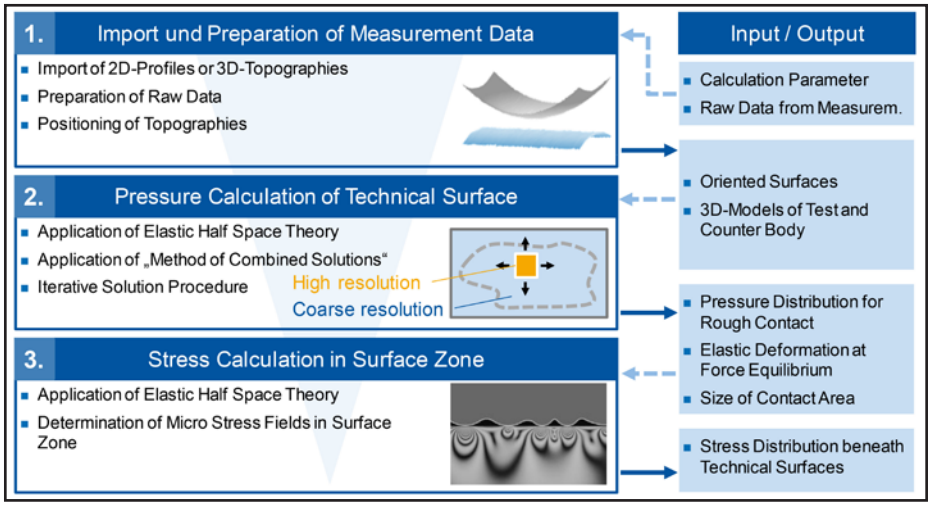

Figure 8 Method for surface stress calculation (Refs. 7, 15).

use of the elastic half-space theory. Due to calculation performance, existing approaches are limited to small sections of the entire contact and use synthetic surface profiles. Therefore, the "Method of Combined Solutions" was developed that allows for contact calculations of large areas with high resolution (Ref. 15). With this method, non-conforming high-resolution grids are used in a specific area and a coarse resolution in all remaining areas. This allows for a detailed analysis of the contact conditions in the area of high resolution without neglecting the stiffness of the other areas of the contact. The area of high resolution is moved step by step over the entire contact area. For each configuration the calculation is repeated. At the end, all high- resolution solutions are combined. The result is a micro pressure distribution of the contact of technical surfaces. In a last step, the stress distribution below the surface is calculated according to the pressure distribution from the second step. The stress distribution is again determined according to the half-space theory. This new contact calculation approach was successfully validated by a comparison of measured and simulated contact patterns and based on the values of the half-axes of the Hertzian contact ellipse.

In a last step the pitting strength calculation was validated. Therefore, a gear was designed to resemble the contact conditions of the disc-to-disc contact ($C\text{-}PT_{mod}$ according to (Ref. 16) modified with high lead crowning) (Fig. 9). This gear was used to investigate the fatigue strength on a back-to-back test rig. As expected, the high lead crowning results in a narrow centered contact pattern, as can be seen in the tests as well as in the FE-TCA. For each contact point on the tooth flank, the probability of survival was evaluated locally (Fig. 9, top right). As expected, the minimum probability of survival occurs in the area of the damage origin. A major goal of the enhanced weakest link model is the consideration of the size effect in strength calculation. Hence, the model approach was applied on two additional test series from the literature (Ref. 17). The two test sets were in a comparable size range regarding the gear macro geometry as the variant (Fig. 9). Nevertheless, the lead crowning in the variants of (Ref. 17) was much, lower leading to a larger zone of applied stresses; consequently, a size influence is addressed. A representative damage and the distribution of probability of survival are shown (Fig. 9, bottom). The area of damage origin and minimum probability of survival are in congruence for this gear set as well.

In Figure 10 the torque levels for a probability of failure of 50% is shown. The same gear geometry 1 with a lead crowning of $C_{\beta 2} = 121\,\mu m$ was used in the investigations. The test bench trials resulted in a torque level of $T_{inp,50\%} = 115\,Nm$. At the same time, the local calculation approach nearly matched that result and predicted a torque level of $T_{inp,50\%} = 123\,Nm$. However, the standard calculation according to ISO 6336-2 predicted a much higher tolerable input toque of $T_{inp,50\%} = 170\,Nm$. The reason for this is the basically non-existent consideration of modifications in the standard calculation. As shown before, the high lead crowning creates a narrow contact pattern that results in a higher Hertzian pressure, which subsequently results in an earlier failure due to contact fatigue. The local FE-based approach can take all modifications into account and, therefore, does not have the same limitations.

Gear geometry 2 was analyzed based on the results found in the literature (Ref. 17). The two investigated test series differed in heat treatment in terms of the case hardening depth chosen. Variant 1 had a case hardening depth of $CHD = 0.68\,mm$ which is equal to $0.14 \cdot m_n$, and therefore in the standard range of $0.1–0.2 \cdot m_n$. The case hardening depth of variant 2 was designed to be larger and out of the standard range. After heat treatment, a case hardening

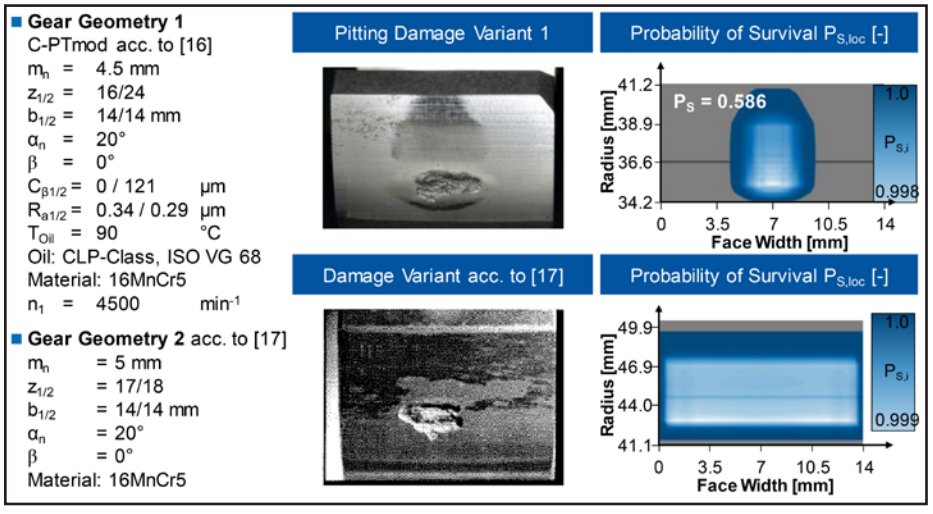

Figure 9 Transfer of local method onto tooth contact.

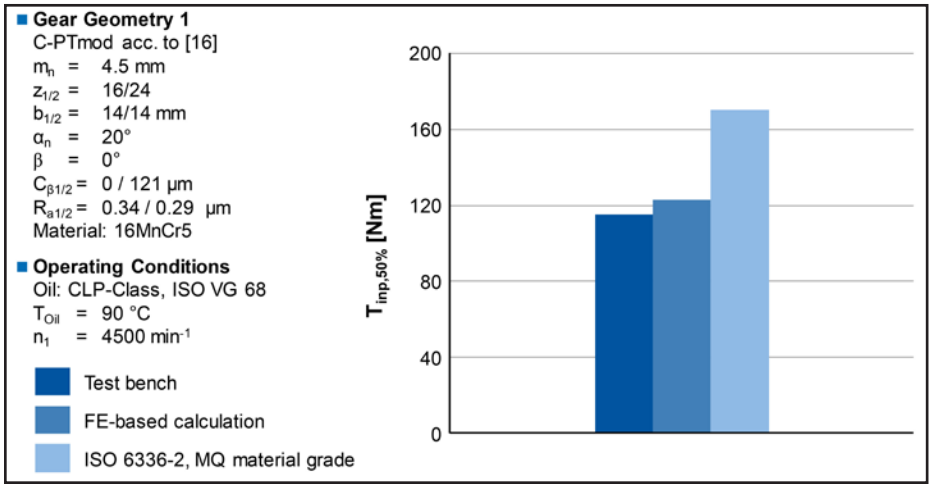

Figure 10 Comparison of calculated and tested fatigue strength ½.

depth of $CHD = 1.46$ mm or $0.29 \cdot m_n$ was measured. In Figure 11, the test bench results are compared to the calculation results for the fatigue strength at 50% probability of failure. The calculations were carried out according to ISO 6336-2, using the average load capability of a MQ grade material and according to the FE-based approach described earlier in this section; the results were transformed to the corresponding torque levels. For heat treatment 1, the calculation according to ISO 6336-2 matches the tested load carrying capacity very well, whereas the simulation suggests a slightly lower load capacity. For heat treatment 2, the opposite is the case. This shows that the ISO 6336-2 standard is quite capable of predicting the gear load capacity for pitting if the gear geometry and material characteristics, e.g. — heat treatment parameters — are close to what was used to derive the standard itself. Outside of that range, a local FE-based approach is capable and more favorable to predict the load carrying capacity correctly.

Tooth root breakage. Following the same principle, in evaluating the local strains and load capacities, the fatigue strength for tooth root breakage can be calculated. This approach was previously described in detail in (Ref. 25). This paper will include a short summary and add a comparison of the results to ISO 6336-3.

Since there is no surface-to-surface contact in the tooth root, the loads regarding Hertzian pressure, thermal loads, and micro Hertzian pressure due to rough surfaces can be ignored. The simplified model to calculate the tooth root load capacity is shown (Fig. 12).

In this report, two types of helical gears were investigated regarding tooth root breakage. The gear data of the two types is shown (Fig. 13). The main difference of the helical gears was the variation of the helix angle. The helix angle was set to $\beta = 20°$ and 33°. The normal module m_n and the pressure angle α were constant for both helical gears. In order to match the center distance of $a = 91.5$ mm of the test bench, the number of teeth and the addendum modification factor of the gears were modified (Ref. 18).

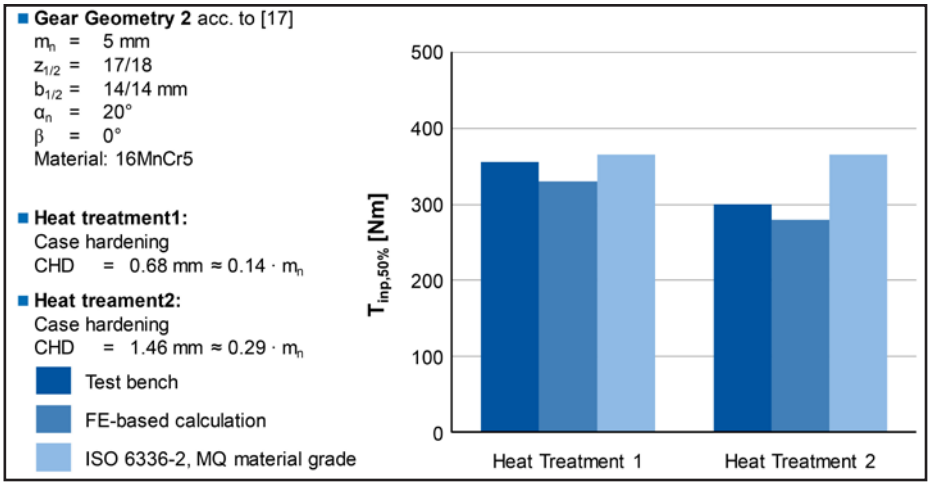

Figure 11 Comparison of calculated and tested fatigue strength 2/2.

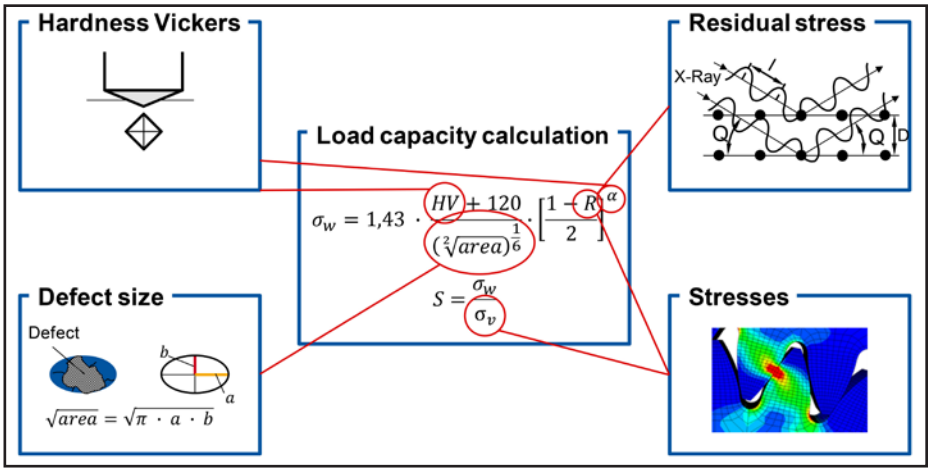

Figure 12 Influencing factors on the load carrying capacity of a defect (Ref. 18).

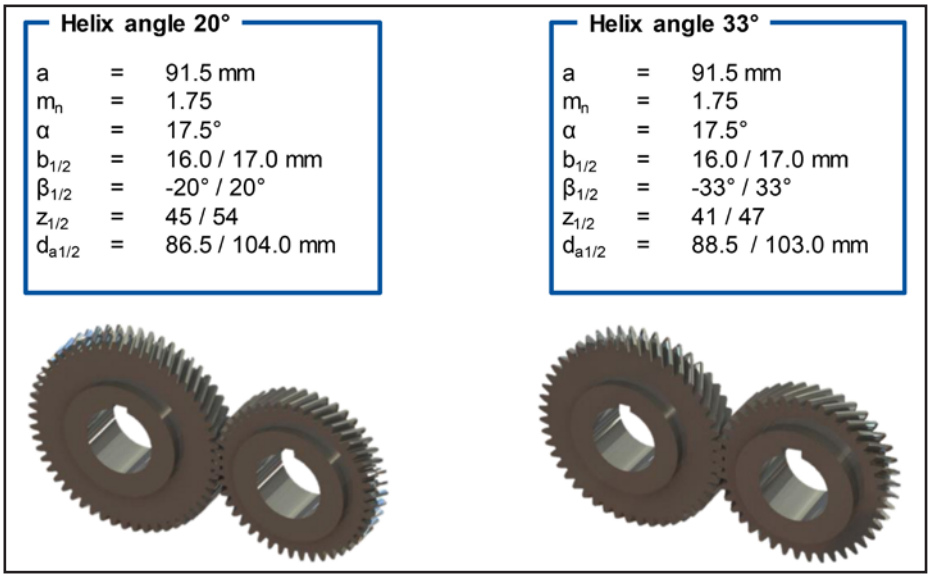

Figure 13 Evaluated gear macro geometries (Ref. 18).

Figure 14 depicts the material properties and defect distribution of the helical gears. The figure shows the Vickers hardness and the residual stresses on the right and the defects and there properties on the left side. The defect size was measured on fractured surfaces, and as the cumulative frequency indicates, it can be described by a Weibull-distribution (Ref. 18).

The comparison of the testing and simulation results for the sample helical gear with a helix angle of $\beta = 20°$ is shown (Fig. 15). The torque level that leads to a 50% probability of failure was evaluated based on the staircase method.

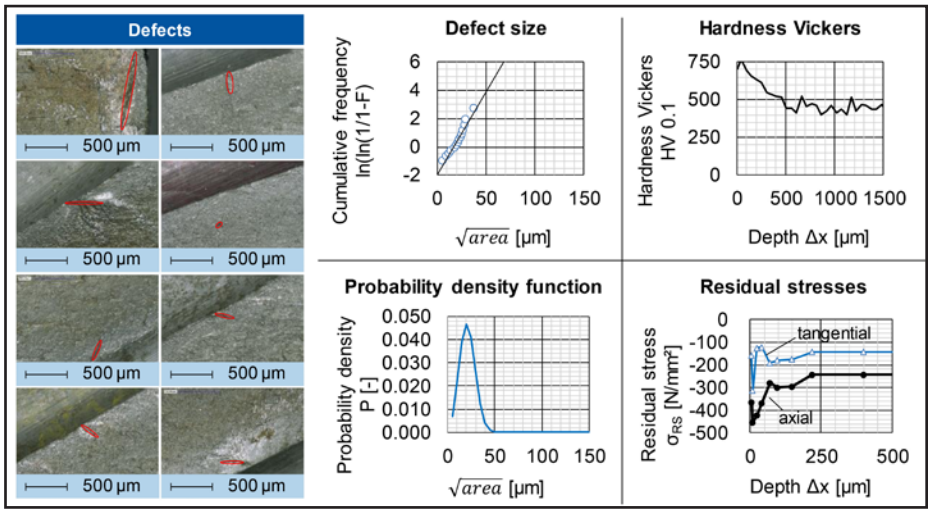

Figure 14 Material and defect characterization (Ref. 18).

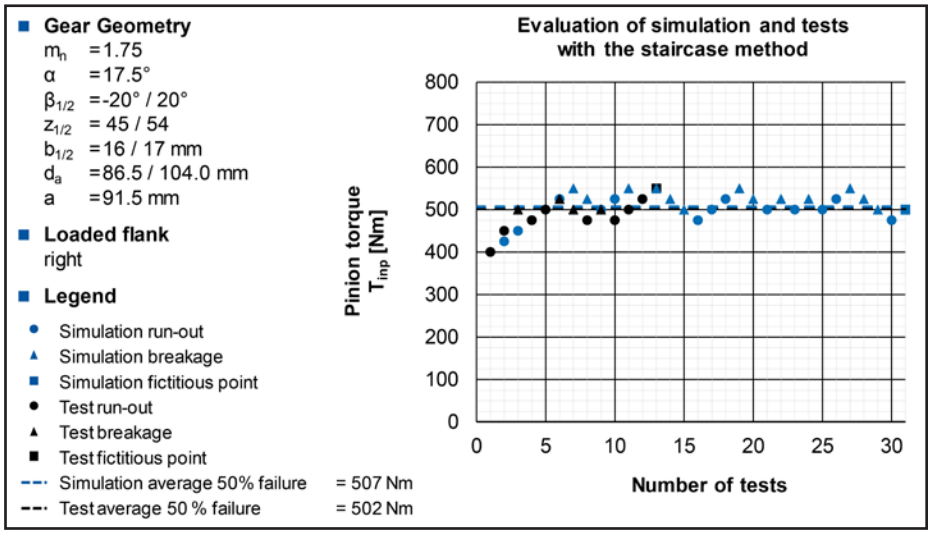

Figure 15 Comparison of the simulation and testing results for the helical gears (Ref. 18).

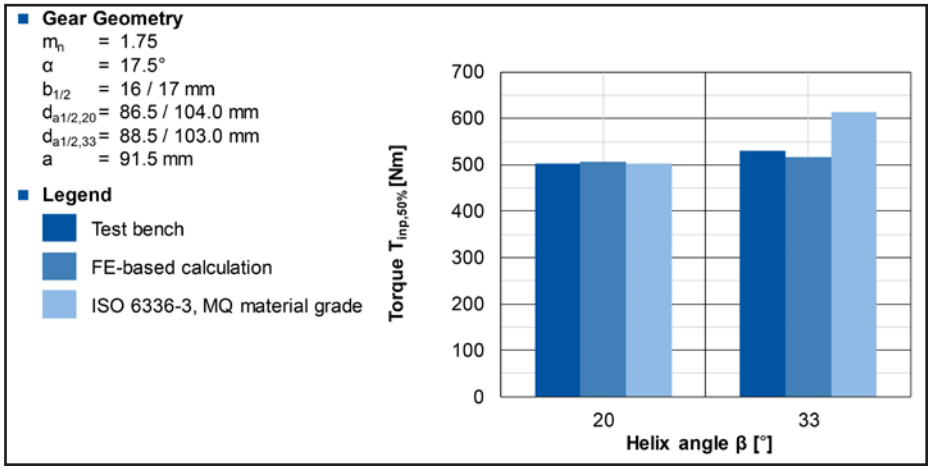

Figure 16 Overall comparison of the simulation and testing results for all tested gears (Ref. 18).

The average torque at the pinion was $T_{inp,50\%,test} = 502$ Nm for the eleven test runs, marked in black. The average torque at the pinion of the simulation was $T_{inp,50\%,sim} = 505$ Nm, marked in blue. The deviation of the two torque levels is less than 1%. The comparison of the results of the helical gear with a helix angle of $\beta = 20°$ shows a very high accordance of the simulation model and the testing results (Ref. 18). The results for both investigated macro geometries are summarized (Fig. 16). The calculation results based on the described FE-approach and ISO 6336-3 are compared to the test bench results.

For both sets, the deviation of the FE simulation and testing results is lower than 2%. It can be concluded that the proposed calculation method is capable of calculating the torque level that leads to a 50% probability of failure for a given gear (Ref. 18). The comparison to ISO 6336-3 shows that the gear with a helix angle of $\beta = 20°$ is represented well by the standard, whereas the load carrying behavior of the gear with a helix angle of $\beta = 33°$ could not be described. The ISO's scope is limited to a helix angle of $\beta = 25°$. Therefore, the ISO standard is not applicable to a higher helical angle, although those are very common, for example, in the automotive industry. The local FE-based method does not have these restrictions by design, and is not limited to an empiric database in terms of gear macro geometry. This enables the local FE-based approach to predict the gear load capacity correctly for arbitrary geometries.

Flank fracture. Flank fractures can occur on cylindrical and bevel gears (Refs. 19–20). These failures are breakages of teeth in the area of the active tooth flank. These fractures have their origin in the inner component volume, usually starting close to the pitch circle and showing a characteristic course of the primary crack of about 45° to the active tooth flank (Ref. 21). In addition to the primary crack, secondary and tertiary cracks are also observed

in existing literature about tooth flank fracture. They arise due to the change in the local stiffness properties caused by the primary crack and run parallel to the tooth tip below the primary crack (Ref. 22). Flank fractures have their crack origin in the inner component volume at a depth that corresponds to about twice the case hardening depth. Often a defect in the structure is discovered at the crack origin. When using case hardening steel 18CrNiMo7-6, those defects mostly consist of aluminum oxides (Al2O3) and when using 20MnCr5 they mostly consist of manganese sulfide (MnS) (Ref. 22). The chemical composition of the defects is irrelevant. Rather, the difference in the Young's modulus between the defect and the steel matrix is considered to be the cause of a stress exaggeration at the defect and an associated crack initiation (Refs. 6 and 22). According to the current flank fracture model that resulted in ISO/DTS 6336-4, the Hertzian pressure has the highest relevance; secondary stresses are not considered directly.

In the existing literature, it is assumed that the primary crack propagates at a characteristic angle of about 45°, relative to the active tooth flank. In case hardened gears the crack starts with a fast growth rate and then slows down towards the component's surface due to the increasing hardness. The crack growth is initially described by fatigue behavior and the associated smooth fracture surfaces and occurring beach marks. After a critical crack length is reached, a force breakage occurs within a few load cycles. In contrast to other tooth flank fatigue damages, a direct failure of the gear stage is associated with the occurrence of flank fracture. (Ref. 22). Figure 17 (right) shows the responsible stresses for flank fractures according to Witzig (Ref. 22).

Compared to pitting damage, stresses in significantly higher depths (approx. a power of ten difference) are crucial. Influences from the friction state and the kinematics are therefore negligible (Ref. 19). Furthermore, the crack initiation location is not in the area of maximum stress, but in the area of lower load capacity (Ref. 20). Therefore, for tooth flank fracture the primary stress caused by the contact pressure, in

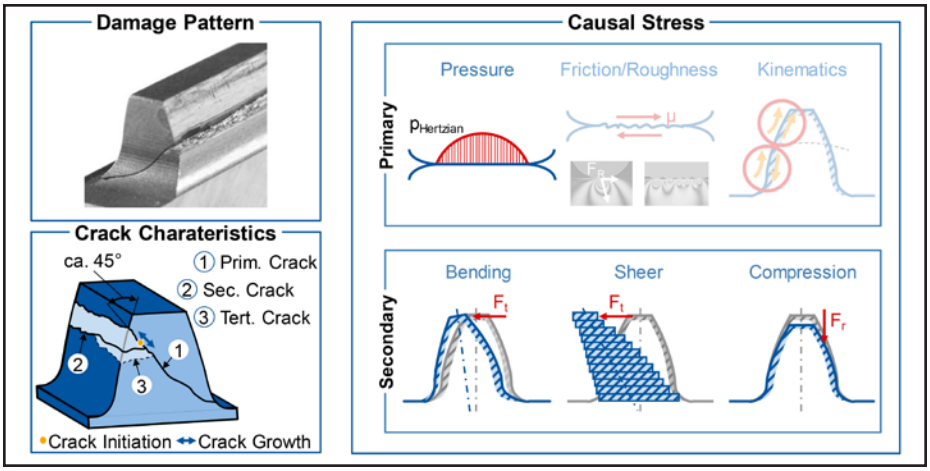

Figure 17 Characteristics of tooth flank fracture (Ref. 22).

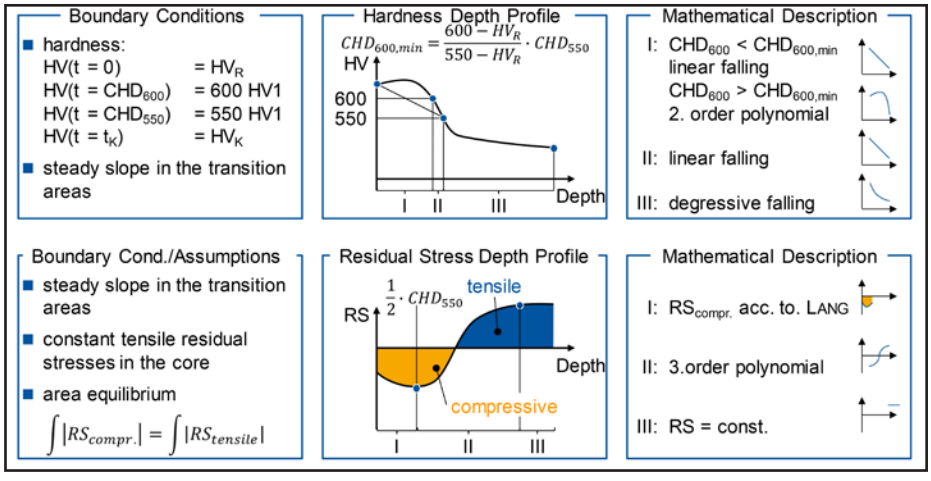

Figure 18 Calculation of tooth flank fracture load capacity (Ref. 23).

combination with the mechanical secondary stress due to bending, shear and compression, is regarded as causative (Refs. 20 and 22).

In this paper, the calculation of the stress present in the tooth volume is performed according to the approach of Konowalczyk (Ref. 23). The FEA is used in order to achieve the highest possible quality of results. A quasi- static simulation of the gear meshing takes into account the influence of the contact pressure with respect to the primary stress. Influences from the friction and the kinematics are considered subordinate, according to the state of the art and therefore are not considered in the simulation. Furthermore, a simultaneous calculation of the secondary load due to bending, shear and compression takes place. By using the general FEA, all stress components are calculated in their entirety. A superposition of simplified models is not necessary. Furthermore, a 3-D strain state is considered.

The result of the stress calculation is the time-dependent stress tensor for each volume element in the tooth. This represents the input variable for the calculation of an equivalent stress. In order to be able to take into account the characteristic rotation of the main axis system of the rolling contact and the time-dependent stress, the SIH is used for equivalent stress formation in this paper, as demonstrated in the pitting fatigue calculation approach (Refs. 7, 9). In contrast to the work of Witzig, however, not only the maximum value of the shear stress of all sectional planes is considered; but there is a differentiated calculation of an equivalent mean stress and the stress amplitudes. This procedure is carried out once taking into account the load-dependent stresses and once taking into account the residual stresses (Ref. 23).

The hardness and residual stress depths are calculated using analytical formulas based on a few input quantities (Fig. 18). First, the calculation of the hardness depth profile takes place. The

calculation requires the specification of an edge hardness HV_R, a core hardness HV_K, a case hardening depth CHD_{550} and an additionally introduced case hardening depth CHD_{600}. The hardness depth profile is divided into three areas, which are defined by the two specified case hardening depths. The boundary condition for connecting the subdivided areas is a continuous slope in the transition areas. Depending on the surface hardness HV_R, the case hardening depth CHD_{600} and the case hardening depth CHD_{550}, a minimum case hardening depth $CHD_{600,min}$ is calculated by assuming a linearly decreasing hardness up to the case hardening depth CHD_{550}. If the specified case hardening depth CHD_{600} is less than the minimum case hardening depth $CHD_{600,min}$, then the first and second regions are summarized by a linear hardness decline (Ref. 23).

If the specified case hardening depth CHD_{600} is greater than the minimum case hardening depth $CHD_{600,min}$, a hardness depth profile with a hardness plateau is assumed. In this case, the first section of the hardness depth profile up to the case hardening depth CHD_{600} is described by a second-order polynomial. The second section between the two case hardening depths is calculated by a linear function. The third area is described by a degressively decreasing hardness towards the core hardness. By specifying the abovementioned variables and the boundary condition of the continuous slopes in the transition areas, the hardness depth profile is mathematically described. The specification of the introduced second case hardening depth CHD_{600} allows, in contrast to approaches used in the state of the art, the differentiated consideration of a hardness plateau.

The calculation of the residual stress depth curve is divided in sections as well. In the edge area up to half the case hardening depth CHD_{550}, the approach according to Lang is used to calculate the residual compressive stresses (Ref. 24). For this depth range, the Lang approach is validated and there are no residual tensile stresses. Subsequently, the estimation of the residual stresses depth profile is carried out via a polynomial of the third order, which describes the transition from the compressive residual stress state into the tensile residual stress section of the residual stress profile. From a certain depth on, constant tensile residual stresses are assumed. The basis for these considerations are the residual stress measurements performed by Witzig using a neutron source (Ref. 22). The amount of residual tensile stresses and the depth at which constant residual tensile stresses are assumed are selected by means of an optimization algorithm in such a way that an equilibrium of compressive and tensile residual stresses results. This approach takes into account the principle of balance forces.

The method for considering defect size and distribution is based on the work of Murakami. This establishes an empirical relationship between the hardness HV, the defect area and the alternating strength σ_w. The method proposed by Murakami has already been extensively validated on simple samples (Ref. 25). Henser successfully used the method in a three-dimensional tooth contact analysis to describe the tooth root load carrying capacity of gears, as demonstrated (Ref. 18). For the representation of the statistical distribution, the calculation of the component's load carrying for flank fracture is also done according to the method of Henser (Ref. 18). In this case a random distribution of imperfections in the tooth volume is generated in successive calculation steps (Fig. 19, top). The random distribution follows a density function of the defects, which results from the degree of purity of the material and is described by the scale parameter T and shape parameter k of a Weibull distribution and a reference number of defects present in the volume. On the basis of the local data regarding the stress, the hardness and the residual stress state, it can be calculated whether a defect causes an exceeding of the local material strength (Fig. 19, bottom-right).

Deviating from the procedure according to Henser, the fatigue strength of a defect is calculated differently in this approach, whereby initially no influence from the locally present mean stresses on the tolerable stress amplitude is considered. This is done in a second step according to the recommendation of Murakami by calculating a mean stress sensitivity (Ref. 25). In this paper the procedure according to FKM is used for the calculation of the mean stress sensitivity (Ref. 12). Since the load-dependent mean stresses are small compared to the residual stresses in the critical region for flank fracture and, furthermore, the sign can be determined for the residual stresses within the SIH only, only the mean stresses resulting from the residual stresses are accounted for.

Based on the strain calculation for each defect in the tooth inner volume, the result of a calculation step is evaluated either as a breakage or as a run out and classified in a simulative stair case method (Fig. 19, bottom left). Based on the result, the load stage for the next step is selected and the load capacity calculation is repeated. The procedure described is repeated a total of 50 times to achieve a high statistical coverage of the result with regard to the mean value and the variance.

First, the simulation was validated using trials from literature (Ref. 22). The

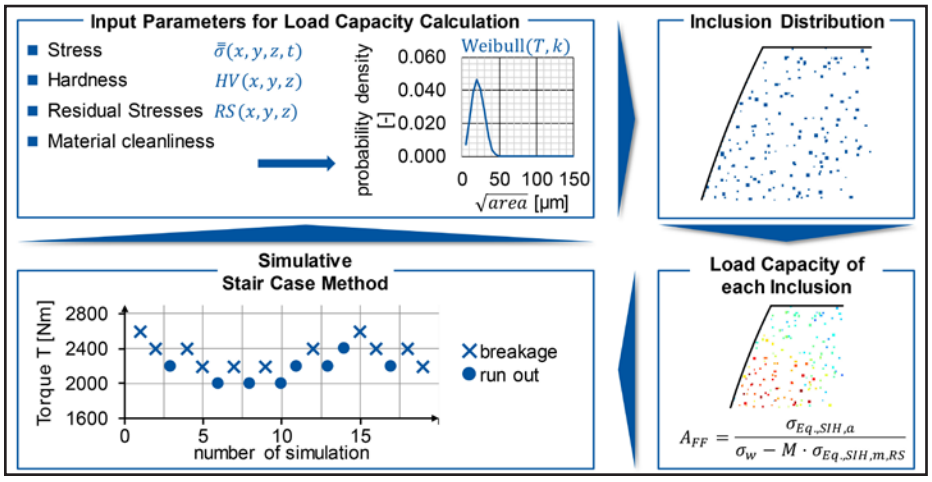

Figure 19 Method for the consideration of inclusion size and distribution.

gear chosen was a straight spur gear with a normal module of $mn = 3$ mm, a number of teeth of $z_{1/2} = 67/69$ and a center distance of $a = 200$ mm. The material used was the case hardening steel 18CrNiMo7-6 for one variant and the case hardening steel 20MnCr5 for the second variant. The edge hardness *HVR*, the case hardening depths *CHD*600 and *CHD*550 and the core hardness *HVK* are shown in Figure 20. Since the inclusion distribution for the given material batch was not available in the publication, a synthetic distribution based on experimental data of a different batch of the same material and on data collection from the pictures in the publication was used. The resulting torque level for a probability of failure of 50% for the test bench trials, the FE-simulation and the ISO/DTS 6336-4 calculation are shown in the upper half of Figure 20. In this case, both the ISO calculation as well was the FE approach match the test bench results with minor deviations. In the lower half, the strain depth profile is plotted and compared to the depth where crack initiation areas were identified. The critical strain for the occurrence of flank breakage is set to $A = 0.8$ for the ISO calculation and $A = 1.0$ for the FE approach. Both methods predict flank fracture correctly and show the strain maxima in the depth where the crack initiation took place. The ISO calculation as well as the FE-simulation tend to predict the critical depth to be on the lower side, with the FE-simulation being more precise for the given case.

To validate the FE simulation with a second gear geometry a straight spur gear with a normal module of $mn = 8$ mm, a number of teeth of $z_{1/2} = 24/25$ and a center distance of $a = 200$ mm was chosen. The material used was the case hardening steel 18CrNiMo7-6. The edge hardness *HVR*, the case hardening depths *CHD*600 and *CHD*550 and the core hardness *HVK* are listed (Fig. 21). The calculations of the fatigue strengths were again performed according ISO/DTS 6336-4 as well as according to the FE-approach described in this paper and both are compared to test bench results. The results demonstrate that the FE-based model is clearly more accurate than the approach according to ISO/DTS

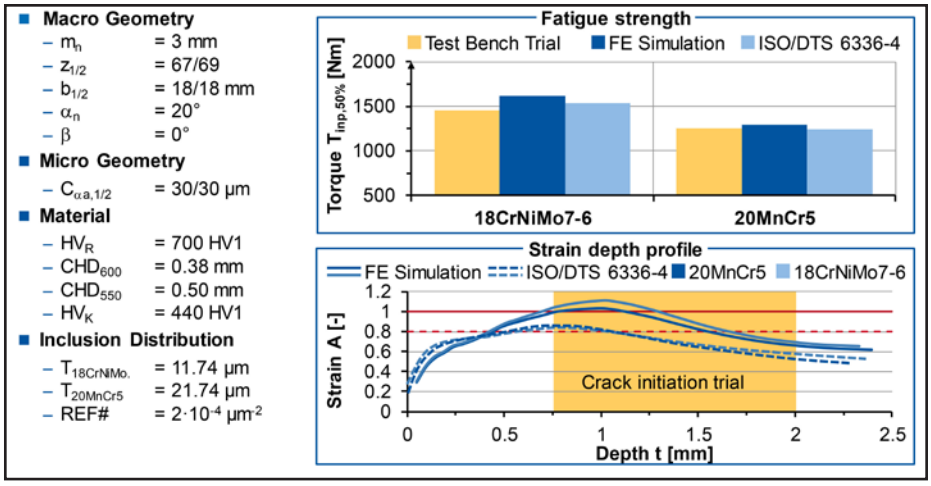

Figure 20 Method validation module 3 mm.

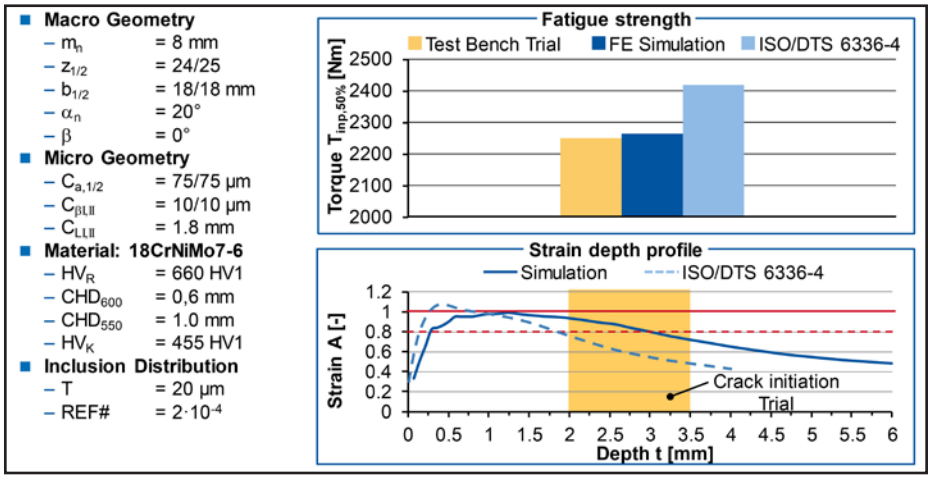

Figure 21 Method validation module 8 mm.

6336-4. The calculation of the strain in the gear according to ISO/DTS 6336-4 shows the highest strain near the surface, Figure 21, lower half. The strain then stays on a high level until a depth of $t = 1.25$ mm is reached. After that, the strain steadily decreases over the depth. The flank fractures occurred during testing had their crack initiation site in depths of $t = 2.0 \ldots 3.5$ mm. Thus, on the one hand, a flank breakage probability is shown by means of the calculation model. On the other hand, the depth of the highest strain does not agree with the test bench results. The same is true for the FE-based approach in terms of the strain prediction.

Although the prediction of the highest strain is closer to the crack initiation area in the FE-based approach compared to the model of ISO/DTS 6336-4, it also shows a lower critical depth by trend. Both approaches should be optimized in the future to improve the prediction of the crack initiation depth for arbitrary gear geometries.

Summary and Outlook

Power density is a key factor in gear design. Increasing the power density enables engineers to use smaller gears for their applications which lead to smaller and lighter gear boxes. The required high power density of the gearbox demands an exact calculation method for the strength against the predominant failure modes of the given gear sets. This includes pitting, tooth root breakage and flank fracture. The precise recalculation of the tooth strength is necessary, as the downsizing leads to a reduction of the remaining safety reserves.

With regards to the calculation of the strength of cylindrical gears a trend towards local calculation approaches is visible. Instead of calculations solely based on standards and global calculation approaches, local approaches based on Finite Element Analysis (FEA) are used. It was demonstrated in this paper,

how FE-based models can be used to predict the most common failure modes pitting, tooth root breakage and flank fracture for a 50% probability of failure.

The prediction of the fatigue strength for pitting and tooth root breakage by the FE-based methods was very accurate for all geometries shown in this paper. It was demonstrated how the ISO standard became very inconsistent with the test bench results when the scope of the standard was exceeded, although the geometries investigated were not uncommon in the gear industry. In contrast to the standard, the accuracy of local FE-based approaches is not directly affected by the gear geometry by design.

For flank fracture the results were not as good as for pitting or tooth root breakage. This is true for the ISO/DTS 6336-4 as well as the FE-approach. Flank fracture has its origin in the inner material volume which increases the difficulty of correctly describing the stress state. For example, there is no viable option to measure the residual stresses in that area. Therefore, more assumptions are used to predict those characteristics. More research needs to go into improving the FE-based calculation methods for flank fracture in particular. Additionally, the validity for a 1% probability of failure needs to be proven.

An additional benefit of the local approaches is the direct consideration of the cleanliness of the steel, which was not targeted in particular in this paper. The downside of the FE-approaches is that the material needs to be characterized well to achieve consistent results. But without material characterization there is no way to achieve the maximum power density independent from the chosen approach. For non-critical low load applications, FE-based methods can offer a tool to predict minimum steel cleanliness in favor to achieve a cost benefit. **PTE**

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For more information.

Have questions or comments regarding this technical paper? Contact WZL's Dr. Christoph Löpenhaus at *c.loepenhaus@wzl.rwth-aachen.de.*

Dr. Marco Kampka is a 2012 graduate of RWTH Aachen University, having studied mechanical engineering with a focus on production engineering. He began his career working in 2012 as a scientific research assistant at the gear department of the Laboratory of Machine Tools and Production Engineering (WZL). In July 2017, he finished his doctoral thesis and joined Fraunhofer CMI in Boston, MA as the head of the gear and transmission technology group. Today, Dr. Kampka is a technical sales manager at Gleason-Pfauter Maschinenfabrik GmbH in Ludwigsburg, Germany.

Prof. Dr.-Ing. Christian Brecher has since January 2004 been Ordinary Professor for Machine Tools at the Laboratory for Machine Tools and Production Engineering (WZL) of the RWTH Aachen, as well as Director of the Department for Production Machines at the Fraunhofer Institute for Production Technology IPT. Upon finishing his academic studies in mechanical engineering, Brecher started his professional career first as a research assistant and later as team leader in the department for machine investigation and evaluation at the WZL. From 1999 to April 2001, he was responsible for the department of machine tools in his capacity as a Senior Engineer. After a short spell as a consultant in the aviation industry, Professor Brecher was appointed in August 2001 as the Director for Development at the DS Technologie Werkzeugmaschinenbau GmbH, Mönchengladbach, where he was responsible for construction and development until December 2003. Brecher has received numerous honors and awards, including the Springorum Commemorative Coin; the Borchers Medal of the RWTH Aachen; the Scholarship Award of the Association of German Tool Manufacturers (Verein Deutscher Werkzeugmaschinenfabriken VDW); and the Otto Kienzle Memorial Coin of the Scientific Society for Production Technology (Wissenschaftliche Gesellschaft für Produktionstechnik WGP).

Dr. -Ing. Dipl. -Wirt. -Ing. Christoph Löpenhaus has since 2014 served as Chief Engineer in the Gear Department of WZL, RWTH Aachen / Laboratory of Machine Tools and Production Engineering (WZL), RWTH Aachen. He previously held positions there as (2011–2014) Team Leader, Group Gear Testing Gear Department Chair of Machine Tools Laboratory of Machine Tools and Production Engineering (WZL) RWTH Aachen; (2010–2011) Research Assistant, Group Gear Testing Gear Department Chair of Machine Tools Laboratory of Machine Tools and Production Engineering (WZL) RWTH Aachen: (2007–2009) as Student Researcher, Group Gear Design and Manufacturing Calculation Gear Department Chair of Machine Tools Laboratory of Machine Tools and Production Engineering (WZL) RWTH Aachen; and (2004–2009) as a student in Industrial Engineering RWTH Aachen.

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Motion Industries

ACQUIRES AUTOMATION AND ROBOTICS COMPANY

Motion Industries, Inc., a distributor of maintenance, repair, and operation replacement parts and a wholly owned subsidiary of Genuine Parts Company (GPC), has announced that it has entered into a definitive agreement to acquire Axis New England and Axis New York ("Axis"), an automation and robotics company based in Danvers, MA.

Founded in 1994, Axis New England serves the Northeast U.S. from its locations in Danvers, MA, and Rochester, NY (Axis New York). With expertise in advanced machine automation, the company will continue its focus on motion control, robotics, and machine vision. Areas of specialty include precision components, electro-mechanical assemblies and fully engineered automation systems.

Todd Clark, Axis president, said, "Motion Industries is a great cultural fit for us. We are pleased to join the Motion team and excited about the growth opportunities this will afford the company and our employees. Our customers and suppliers can expect the same partnership, support, and service as we continue our focus on delivering high-value solutions."

"We are very pleased with the addition of this well-established company, which will operate as part of Motion's Automation Solutions Group," stated Randy Breaux, president of Motion Industries. "Acquiring Axis is in keeping with our strategic intent and complements our growth in the area of industrial plant floor automation. We welcome the Axis employees to the Motion Industries family and we look forward to the contributions they will make to our Company in upcoming years." (*www.motionindustries.com*)

Lenze Americas

HOSTS STEM CAREER DAY FOR LOCAL STUDENTS

Lenze Americas**,** a manufacturer of electrical and mechanical drives, motion control and automation technologies, welcomed students from local middle schools on Thursday, February 7, 2019 to its North American headquarters in Uxbridge, Massachusetts. This event was co-sponsored by the Blackstone Valley Education Foundation (BVEF) and enabled students to explore possible STEM career paths in manufacturing.

"We enjoyed opening our doors to the young people in our community to provide a glimpse of what a career in manufacturing and engineering looks like today. It was a pleasure hosting the local students and educating them on the important role our industry plays in our economic future. Some members of this group will be our future engineers, so we were happy to have them join us to participate in exciting learning activities, talk with current staff engineers, and tour our manufacturing facility," said Floyd Spencer, sales and technical training manager, Lenze Americas. "We received nothing but positive feedback from teachers and students, and look forward to working with BVEF to host similar educational events in the future."

Students toured Lenze Americas production floor and were introduced to Lenze Americas as a local manufacturer with global reach. Lenze Americas staff and management also talked about the various career opportunities for engineers within the organization's business functions. Seasoned and new engineering professionals provided insights into potential career paths while sharing what attracted them to engineering and the manufacturing field. (*www.lenze.com*)

John Malinowski

NAMED 2019 IEEE FELLOW

John Malinowski, senior manager of industry affairs (retired from Baldor Electric Company), of Fort Smith, Arkansas, has been named an IEEE Fellow. He is being recognized for contributions to motor efficiency manufacturing regulations and standards.

The IEEE Grade of Fellow is conferred by the IEEE board of directors upon a person with an outstanding record of accomplishments in any of the IEEE fields of interest. The total number selected in any one year cannot exceed one-tenth of one-percent of the total voting membership. IEEE Fellow is the highest grade of membership and is recognized by the technical community as a prestigious honor and an important career achievement.

Malinowski is immediate past chairman of NEMA MG1 Motor and Generator Section, and Baldor's representative energy advocate organizations. Malinowski is a senior member of IEEE, a member of the IEEE Industry Application Society and past Director-at-Large of IEEE IAS Executive Committee. He is a member of the IEEE Pulp and Paper Industry Committee and Past Chairman for the Forest Products and Drives & Control Systems Subcommittees. Malinowski is also active with IEEE Petroleum and Chemical Industry Committee and serves on several IEEE Standards Working Groups. He has published several articles in leading industry publications on motor and drive efficiency, maintenance and applications. He acts as company advocate with government agencies, professional associations and industry standards committees.

The IEEE is the world's leading professional association for advancing technology for humanity. Through its 400,000 plus members in 160 countries, the association is a leading authority on a wide variety of areas ranging from aerospace systems, computers and telecommunications to biomedical engineering, electric power and consumer electronics.

Dedicated to the advancement of technology, the IEEE publishes 30 percent of the world's literature in the electrical and electronics engineering and computer science fields and has developed more than 1,300 active industry standards. The association also sponsors or co-sponsors nearly 1700 international technical conferences each year. (*www.ieee.org*)

KTR Corporation

NAMES MARCOS NEW CEO

Marcelo Marcos has been named president and CEO of KTR Corporation. Marcos was the marketing manager from 1995 to 2002. "Around 2000, Jerry Elenz, KTR's founder, retired and my personal goal evolved into one day leading KTR Corporation, but due to my young age and limited general business experience at the time, I kNew I needed an opportunity to grow," said Marcos.

In 2002, Marcos was tapped to start up KTR Brazil and he was ready for the challenge. "I accepted the opportunity to start up KTR Brazil, kNowing I would gain invaluable experience and strengthen my skills selling the company in a new untapped market," he added.

Marcos has developed KTR Brazil into a solid and aggressive company whose biggest trademark is service — outperforming competitors in agility and quality.

"KTR Corporation is home professionally speaking! 23 years ago, I started with the goal to help the company grow into Latin America. I think we succeeded in this task," Marcos said.

The retirement of KTR Corporation's President William Ketcham at the end of 2018 brought Marcos the opportunity to come full circle. Marcos plans to capitalize on the accomplishments reached during Ketcham's tenure and add his own motivation and intense sales focus to lead KTR Corporation to great success. (*www.ktr.com/us*)

Alliance Sensors

PARTNERS WITH DIGI-KEY ELECTRONICS

H. G. Schaevitz LLC dba Alliance Sensors Group is pleased to announce a partnership with Digi-Key Electronics, Thief River Falls, MN, to distribute its line of LVIT linear position sensors. Digi-Key Electronics has been committed to offering the broadest selection of in-stock electronic components and is pleased to include ASG's line of LVIT sensors to their product offering.

Alliance Sensors Group, founded by the Schaevitz family, has continued to expand its line of linear position sensors using LVIT Technology reaching into the automation and fluid power market places as well as power generation and

civil engineering. The LR and LV series of LVIT products are inductive, contactless devices with excellent stroke-to-length ratio giving a clear advantage over resistive potentiometers.

"Alliance Sensors is excited to partner with a sales channel as prominent as Digi-Key. We feel they can help us target the Automation marketplace in ways we could not handle directly," says John Matlack VP of sales and marketing for ASG. (*www.alliancesensors.com*)

Nidec and Bartholet

SIGN TRADE AGREEMENT

Nidec ASI, head of the Nidec Industrial Solutions platform belonging to the Nidec Group, and Bartholet (Bartholet Maschinenbau AG), a leading company in the field of ropeway systems, have signed a new multi-year trade agreement, which will run until 2022, for the construction and sale of ropeways all over the world. More specifically, Nidec ASI will supply Bartholet with automation and control systems as well as the motors and inverters needed to build future installations worldwide.

After 10 years of fruitful collaboration on the market between the two companies, this partnership renewal will allow Bartholet to become even more competitive, especially outside Europe, thanks to the technical and commercial support provide by Nidec ASI, thus consolidating its position as a leading company in this market. The Group will in fact give Bartholet the opportunity to use its commercial offices and spare parts storage facilities in its Italian and international premises, benefiting from the Group's capillary set-up and efficient after-sales assistance for all the new systems installed.

The agreement includes the development of aerial cableway projects, for both mountain lift services and urban transport, as with the cable-car line inaugurated in Moscow for the 2018 FIFA World Cup, which today makes 3 stops and travels at a height of 50 meters over the Moskva river, transporting fans and tourists between the viewing point near the Moscow State University (MSU) and the Luzhniki Stadium.

In particular, this partnership was created with the aim of increasing the presence of Nidec ASI and Bartholet in markets where the ropeways sector for transporting people is growing the fastest, such as in China, South Korea and countries in the Middle East where over the next few years important projects will be realized involving the expertise of both companies.

"For us this agreement represents an important springboard for the development of ropeway projects around the world. It will give us the opportunity to show our capabilities and support the growth of Bartholet in Russia and Asia (China, Korea and the Philippines). We strongly believe in this collaboration, because the union of our expertise can provide customers with the most advanced and tailor-made solutions. And the first results are proving us right," declared Dominique Llonch, CEO of Nidec ASI. "Thanks to this opportunity, we are aiming to double our business in this sector by 2022, increasing not only our stock of spare parts and our assembly capabilities but, above all, investing in people and strengthening our local teams of engineers who will offer in situ service activities."

An agreement which fully responds to Nidec ASI's strategy and which, thanks to the kNow-how gathered in over 150 years of technological innovation and an engineered-to-order approach, makes it possible to meet the needs of customers all over the world, providing unique solutions with very different technical specifications that can be adapted to every requirement. (*www.nidec.com*)

Bonfiglioli

IMPLEMENTS CERTIFICATION FOR ITS BEST DISTRIBUTORS

With over 550 partners in the world that supply ready-to-use products and aftersales services, industrial distribution has always been a key pillar of Bonfiglioli's business model and a vital corporate asset to better serve its customers.

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In 2019, Bonfiglioli decided to move a step forward alongside its BEST distributors, developing a unique certification in cooperation with TÜV Italia.

The certification is issued by TÜV Italia and guarantees the same high level of worldwide service to all Bonfiglioli customers, when visiting a BEST-certified distributor. The products and services supplied perfectly match Bonfiglioli's quality, environment, security and ethical requirements.

TÜV Italia is an independent certification, inspection, testing and training provider, which offers quality, energy, environment and safety certification services. The auditing carried out by them is based on measurable and repeatable indicators that allow an accurate evaluation of the competence and quality of each candidate. (*www.bonfiglioli.com*)

AD & IDI

MERGE TO BECOME AD CANADA INDUSTRIAL & SAFETY

AD recently announced the merger with IDI Independent Distributors Inc., effective April 1st, 2019. IDI brings 107 independent industrial Canadian distributors with over 364 locations into the AD family. AD also welcomes 21 new employees and a distribution center located in Mississauga, Ontario as part of the transaction. This is AD's ninth merger since the group's founding and its fourth merger within Canada. AD completed mergers with Canadian electrical groups in 1993 and 2012, and a Canadian plumbing & heating group in 2016. AD Canadian members represent 20% of AD consolidated sales.

Coming on the heels of AD's January 1st, 2019 acquisition of the IDC-USA group, the IDI merger further enhances the group's private label and redistribution capabilities, reaffirms AD's commitment to independent industrial distribution throughout North America and reinforces the value of single industry groups coming together under the AD multi-industry umbrella.

Steve Drummond, board chairman of IDI and president of Source Atlantic shares, "On behalf of the 100+ IDI members, we are proud to join this group of best-in-class independent distributors and supplier partners. The IDI members will now get the best of both worlds; programs and services we value from IDI, and the multi-divisional scale and infrastructure of AD."

Drummond continues, "We are also very fortunate that AD has the resources and the experience to seamlessly accomplish a merger of this size. Source Atlantic has benefited from two AD mergers. We first joined the group when AD merged with our former electrical group, and then our former plumbing & heating group joined AD, so I speak from experience when I say that AD kNows how to do mergers right."

As a part of the merger, IDI President Rob Dewar will take on the role as president of AD Canada Industrial & Safety.

Rob Dewar says, "The programs that AD offers to help their members compete today and into the future, cannot be replicated without the scale, and program innovation that AD provides. A great example is the significant investment that AD continues to make in eCommerce, this investment is unparalleled and will be a true game changer for the new members of AD Canada Industrial & Safety," Dewar says.

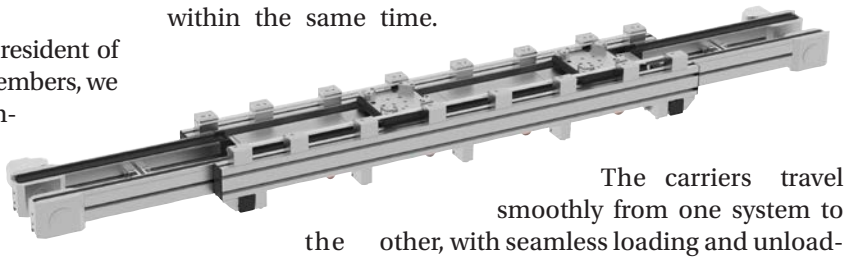
Jack Templin, AD chief programs officer and industrial president, shares, "We are honored to welcome IDI members, suppliers and staff into the AD family. The members are Canadian owned and operated entrepreneurs, local market leaders focused on strong service with a desire to collaborate and share best practices. This merger expands AD Industrial's footprint in North America, our range of services, and helps us to continue to create a winning environment for independent distribution." (*www.adhq.com*)

Siemens and Festo

COLLABORATE ON LINEAR MOTOR DRIVE AND CONTROL CONCEPT

Siemens and Festo are presenting an innovative linear motor drive and control concept, designed to offer flexible and efficient high-performance solutions for short-cycle applications. The Multi-Carrier-System (MCS) from Siemens and Festo has been integrated into the Rexroth TS 2plus transfer system, thus adding the modular MCS to Bosch Rexroth's versatile building-block system based on standardized units. The advantages of the existing systems have been merged, and users are free to combine them in almost any way they wish to achieve maximum flexibility in their processes. This opens up new possibilities in assembly technology or in battery production, for example.

The Multi-Carrier-System enables carriers be accelerated, moved and precisely positioned independently of one another on the MCS track. This not only means that different product formats can be manufactured on a single production line, but also that much shorter cycle times and higher production volumes can be achieved within the same time.



The carriers travel smoothly from one system to the other, with seamless loading and unloading. They can also be integrated into existing intralogistics systems.

Linear motors from Festo form the technical basis for the Multi-Carrier-System, ensuring free and dynamic movement as well as precise positioning for the direct transport of products weighing up to 50 kilograms. Thanks to holistic engineering from Siemens and the integrated motion control functionality provided by *Simotion* and *Simatic*, movement can be controlled precisely and different machine modules can be coordinated within a single system. The Multi-Carrier-System can be seamlessly integrated as part of a digital transformation process – irrespective of the industry or the company size, since kinematic data is already available in a digital format. These data can be directly used to program the controller, for example, resulting in shorter commissioning times.

The Rexroth TS 2plus transfer system is designed for transporting carriers. It comprises standardized building blocks that can be flexibly combined to create a complete system. The modular design enables manufacturers to exploit potential for increased efficiency at a reasonable cost. All of the components feature a particularly rugged design and ensure increased operational stability. (*www.siemens.com/mcs*)

PTDA

REPORTS GROWTH IN 4Q18, SLOWING TREND FOR 2019

The fourth quarter 2018 Sales History & Outlook Report (SHOR) released by the Power Transmission Distributors Association (PTDA) indicates the average PTDA distributors' index for total sales during 4Q18 was 5.4 percent higher compared to 2017. PTDA manufacturers' index annual average was also strong, up 7.3 percent year over year in December. Leading indicators suggest the Index annual average will decline mildly in 2019.

The 4Q2018 PTDA Business Index moved downward to a reading of 57.9 compared to the third quarter reading of 63.1 but still remains slightly above ISM's U.S. Purchasing Managers Index (PMI) of 56.6. The overall trend indicates slowing growth ahead for PTDA member sales.

PTDA members participating in SHOR receive the results and forecasts through 2020 at no charge after the close of the calendar quarter. For more specifics on the forecast for power transmission/motion control sales through distribution as well as forecasts for manufacturer sales, purchase the 4Q2018 SHOR at ***ptda.org/SHOR***.

The PTDA Business Index is modeled after the widely respected PMI and tracks change in business activity, new orders, employment, supplier deliveries, inventories, prices and backlog in the PT/MC industry to arrive at an overall index. The entire 4Q2018 PTDA Business Index report is available through PTDA's website at ***ptda.org/Index***. (*www.ptda.org*)

Eriez

PROMOTES KLINGE TO DIRECTOR, STRATEGIC SALES-AFETRMARKET

Senior Sales Director of Eriez-USA Dave Heubel announces that John Klinge has been promoted to the newly created position of director, strategic sales-aftermarket. In this role, Klinge will head Eriez aftermarket business, which includes the company's service, repair and spare parts departments. Klinge will be responsible for developing key sales strategies, tactics and action plans to expand all facets of Eriez' aftermarket business.

Heubel says, "During his career with Eriez, John has consistently demonstrated an unrelenting drive and commitment to continuous improvement. He has a proven ability to bring out the best in his team and exceed sales goals." He adds, "We are confident that Eriez' aftermarket business will grow and thrive under John's direction."

Klinge joined Eriez in 2008 as a technical sales representative and has excelled and earned consistent promotions. Most recently, he served as light industry market manager. His many achievements in his 11 years with Eriez include spearheading the development and release of the company's extremely successful latest generation Xtreme Metal Detectors.

Prior to his employment with Eriez, Klinge served as a captain in the U.S. Army. He earned bachelor's degrees in political science and business as well as military science from the University of Pittsburgh. He also holds a master's degree in business administration from Penn State Erie, The Behrend College. (*www.eriez.com*)

Whittemore

ADDS PARTNERSHIPS WITH NSK AND LYNDEX-NIKKEN

As of January 14, 2019, The Whittemore Co. (Whittemore) announced that it has officially partnered with NSK America, to its portfolio of products and principals it represents in the states of Illinois and Wisconsin.

NSK America provides high-speed precision machine tool spindles and hand tools to meet the demands of today's critical requirements for many industries including medical, aerospace, automotive, mining and construction, agricultural, electrical, food service and others.

As of January 14, 2019, The Whittemore Co. also announced their partnership with Lyndex-Nikken. Whittemore would represent Lyndex-Nikken in the following states: Minnesota, North Dakota, South Dakota, Iowa, Nebraska, Missouri and Kansas.Lyndex-Nikken is an international company that provides machine tool accessories live and static tools, shrink fit tools, modular and right-angle heads, rotary tables, presetters, toolholders, collets and accessories. (*whittemore-inc.com*)

April 1–5—Hannover Messe 2019 Hannover, Germany. In 2019, the integration, digitization and interconnection of industrial technologies will transform the world's manufacturing industries more than ever before. In recognition of this, the Integrated Automation, Motion and Drives (IAMD) show at Hannover Messe will feature the full range of products and solutions for the factory of the future, including factory and process automation systems, industrial IT, robotics, smart drives, and intelligent hydraulics and pneumatics systems. The unifying theme this year, "Industrial Intelligence," will focus on eliminating production downtime and ensure the seamless integration and operation of all the parts that make up smart factories. Companies like Siemens, ABB, Festo, Bosch Rexroth, Schneider Electric, Phoenix Contact and Beckhoff – have already registered display space. Confirmed exhibitors of intelligent power transmission and fluid power technology solutions include SEW Eurodrive, Schaeffler, Continental, Aventics, Hydac, KTR, Parker Hannifin, Trelleborg and ZF Friedrichshafen. For more information, visit *www.hannovermesse.de*.

April 8–11—Automate 2019 McCormick Place, Chicago. Held once every two years, Automate features the latest in cutting-edge robotics, vision, motion control, and related technologies, the event attracts thousands of visitors from around the world looking for ways to enhance their processes, improve product quality, lower costs, and sharpen their competitive edge. More than 400 exhibitors participate with technologies in drives, motors, actuators, robots, controls, metrology equipment, sensors, software, system integrators and more. For more information, visit *www.automateshow.com*.

April 8–14—Bauma 2019 Munich, Germany. Bauma 2019 is a complete overview of the construction, building materials and mining machinery industry giving attendees access to existing and new markets and contacts with experts and decision-makers with a pronounced willingness to invest. The show brings together international key players and offers access to all markets and target groups giving attendees a complete overview of all innovations, technologies and trends. The show boasts 600,000 participants, an updated floor layout and even more space making it one of the world's largest meeting places for the construction and mining industry. Efficiency, digitization and sustainability will be key focal areas during this year's show. The Bauma Forum is where exhibitors, trade associations and partners present the latest product developments, trends and market analyses in presentations, press conferences and/or panel discussions. For more information, visit *www.bauma.de*.

May 6–9—AISTech 2019 Pittsburgh, PA. This event will feature technologies from all over the world that help steel producers to compete more effectively in today's global market. AISTech is a can't-miss event for anyone involved at any level of today's steel marketplace, providing perspective on the technology and engineering expertise necessary to power a sustainable steel industry. More than 8,000 people are expected to attend AISTech 2019. Along with over 500 exhibiting companies, AISTech 2019 allows attendees to meet face-to-face with key individuals involved in the production and processing of iron and steel. For more information, visit *www.aist.org*.

May 6–9—OTC 2019 Houston, Texas. The Offshore Technology Conference (OTC) is where energy professionals meet to exchange ideas and opinions to advance scientific and technical kNowledge for offshore resources and environmental matters. Celebrating 50 years since 1969, OTC's flagship conference is held annually at NRG Park (formerly Reliant Park) in Houston. OTC has expanded technically and globally with the Arctic Technology Conference, OTC Brasil, and OTC Asia. OTC gives you access to leading-edge technical information, the industry's largest equipment exhibition, and valuable new professional contacts from around the world. Its large international participation provides excellent opportunities for global sharing of technology, expertise, products, and best practices. OTC brings together industry leaders, investors, buyers, and entrepreneurs to develop markets and business partnerships. For more information, visit *2019.otcnet.org*.

May 13–16—CTI Symposium USA Novi, Michigan. The CTI Symposium USA is the International Congress and Expo for Automotive Transmissions, HEV and EV Drives. The event features a two-day introductory seminar, a transmission expo, evening networking party and test drives for the latest development cars. Participants include automotive suppliers, transmission manufacturers, OEMs, metal processing, mechanical engineering and others from North America, Europe and Asia. Topics include powertrain technologies, hybrid transmissions, future considerations, commercial vehicles, starting devices, manufacturing and more. Autonomous driving, NVH, tools and performance forecasting will also be discussed. Speakers this year include Dave Filipe, vice president, global powertrain engineering, Ford, Mayank Agochiya, managing director at FEV Consulting, Inc., Mamatha Chamarthi, CDO at ZF, Stephan Tarnutzer, president, AVL Powertrain Engineering, Inc. and many more. ***Gear Technology*** and ***Power Transmission Engineering*** are co-sponsoring this event. For more information, visit *www.transmission-symposium.com/usa*.

May 20–23—AWEA Windpower 2019 Houston, Texas. Windpower 2019 is the wind industry's premier North American event with wind energy professionals from all over the world gathering in one place. It's the most effective way for attendees to expand their kNowledge base and business network. With competitive pricing and stable policy in place, the wind industry is booming. Now the industry can focus on the future and the other drivers that will propel the industry forward through the 2020s. The program will feature speakers with "disruptive" and innovative ideas that will continue to strengthen wind energy's value proposition and challenge the current way we do business. Attendees will hear about how technology advances will continue to lower LCOE, and learn lessons from other industries that are more mature or have experienced similar rapid growth. They will also receive updates on: state policy support, transmission infrastructure efforts, and emerging and growing offtake trends. For more information, visit *www.awea.org*.

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No Regrets over this Lost Opportunity

Jack McGuinn, Senior Editor

The NASA Mars rover Opportunity; it landed on Mars in 2004 and proceeded to cover 28 miles on the Red Planet — lasting well beyond its expected 90-day mission (Photo AFP/NASA).

It was recently announced that the planet Mars has at least one thing in common with planet Earth — all good things come to an end.

In this case, the good thing is the recently announced and documented (Feb. 12) demise of the Mars rover Opportunity. NASA launched the rover in 2003 for a 3-month mission that improbably lasted almost 15 years (Opportunity's sibling — Spirit — hung on until 2011.).

Yes, the intrepid rolling robot that spent 15 years scouring the surface of the Red Planet for information and beaming it back to NASA is no more. Thomas Zurbuchen, head of NASA's science missions, made the announcement at the space agency's Jet Propulsion Laboratory in Pasadena, California. What ensued was a rather solemn memorial service commemorating "our beloved Opportunity."

Apparently concerns were raised last June when Opportunity's earthbound handlers received a transmission (the final one, as it turned out) that "started to look worrying." The rover reported that its batteries were running low and — not unlike a death scene in a bad movie — "it was getting dark." Some months later Opportunity "was swallowed by a dust storm that took over the entire planet."

There had been NASA efforts to resuscitate Opportunity — to no avail.

The end elicited comments that even HAL would take to heart, such as — "This is a hard day," said project manager John Callas a gathering of hundreds of mourners that oversaw Opportunity (and its long-deceased — if less remembered — identical twin, Spirit). "Even though it's a machine and we're saying goodbye, it's still very hard and very poignant. But we had to do that. We came to that point."

But that was only a small part of the final sign-off, as many other expressions of grief orbited the Twittersphere, e.g.:

Writer Jocelyn Rish tweeted how she "never imagined" she'd "be sitting at my computer crying over a last message from a robot on Mars, but here I sit wiping away tears. Job well done, Oppy."

Graphic designer Dan Mason cited Dylan Thomas to express his regrets, tweeting:

"Do not go gentle into that good night,
Old age should burn and rave at close of day;
Rage, rage against the dying of the light."

And Sulu (you may know him as George Takei), helmsman of the Enterprise, also weighed in: "A sad, sad development for Opportunity and for NASA. Perhaps one day we shall find you again, friend, when humans finally set foot on Mars." (But nothing from Captain Kirk.)

This from Dr. Tanya Harrison, director of research at ASU NewSpace, who described the mood at the propulsion laboratory as the end became clear, Tweeting — "There was silence. There were tears. There were hugs. There were memories and laughs shared."

For instance, according to Steve Squyres, the Mars Rover Mission's principal investigator, "Back in the early days of the mission, we instituted Rover wake-up songs for fun. So we'd play a song each morning (to waken) the rover." But by the end, no music — from the Rolling Stones to Motley Crue — was capable of rousing Opportunity.

Squyres was asked to identify any favorite photos or transmissions received from Opportunity and Spirit.

"They sent back so many things over the years, it's hard to pick a favorite. It really is just the accumulation of 15 years of beautiful data. There were other certainly ones that were surprises. I remember the first time we found a meteorite. Probably my favorite image of the entire mission came on the 12th day of Spirit's mission, when we took a picture looking back at our first ever real tracks on Mars. We had all six wheels on Martian soil, and that for me was the culmination of 16 years of trying to make something like that happen."

But after 15 successful years in operation, "We tried everything we could think of to make contact with Opportunity and didn't get any contact," said Squyres, "We sent our final command to the vehicle, and I was asked by the team to choose what would be the final musical communication. (I) settled on "I'll Be Seeing You" by Billie Holiday." It's final verse:

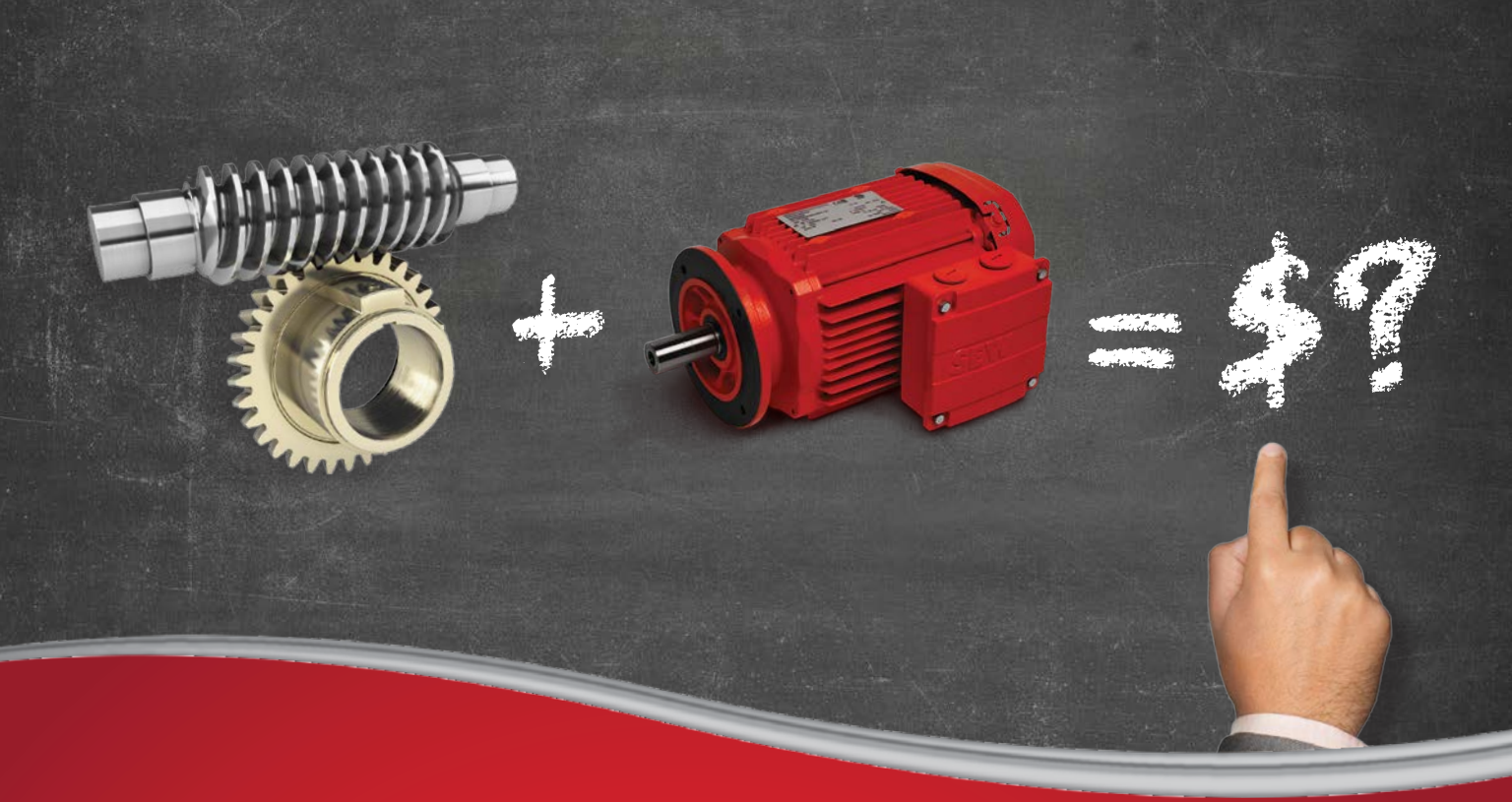
I'll find you in the morning sun
And when the night is new
I'll be looking at the moon
But I'll be seeing you

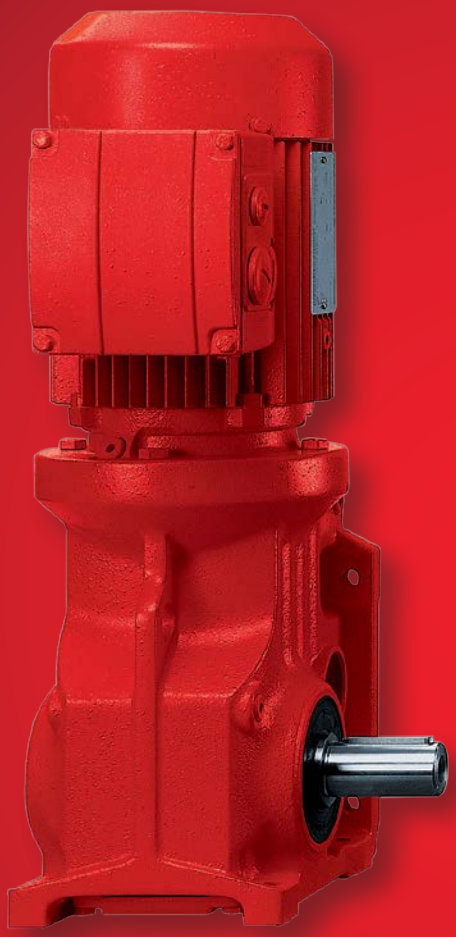
Or as yet another Twitter user (dutchess-becky) put it binarily:

"Dear Opportunity, 01000111 01101111 01100100 01110011 01110000 01100101 01100101 01100100 00100000 01001111 01110000 01110000 01111001, from A Martian Fan."

Or, in short: "Godspeed Oppy." **PTE**

(*Sources: MarsNasa.gov., Wikipedia and NYTimes.com.*)





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