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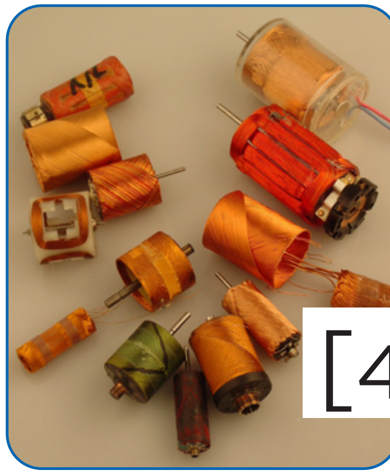

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PTE Videos
Igus Energy Chains

Product Manager Dan Thompson gives an overview of the Igus energy chain product line and discusses the different types of cable carriers available as well as their advantages. Learn more here:

www.powertransmission.com/videos/Energy-Chains-with-igus-/

SKF Aerospace Components

The race for the next generation of aircrafts is on, and major investments are being made into both technology and design developments for the future. Enter the world of aerospace solutions and catch up on all the latest developments from SKF here:

www.powertransmission.com/videos/SKF-Aerospace-Components-/

Editor's Choice

Condition Monitoring with ABB

The PTE September coverage in print and online examines condition monitoring advancements for bearings. We recently discussed some of these innovations with Artur Rdzanek, global product manager, sensored products, at ABB.

www.powertransmission.com/blog/condition-monitoring-with-abb/

Digital Events: Bearing World

Bearing World focuses on all facets of bearings and all involved components, with special emphasis on rolling bearings—in combination with or comparison to plain or magnetic bearings. The conference examines everything from life and durability to lubrication, NVH and smart bearings. Learn more here:

www.powertransmission.com/news/10201/Bearing-World-by-FVA/

Randy Stott
Publisher & Editor-in-Chief

Bearings and Motors and Gears

Oh my. It's been another busy month here at *Power Transmission Engineering*, and we have another full issue for you.

This time around we have a focus on bearings, with plenty of great examples of applications and technology from the world's leading manufacturers. Of course, bearings are essential to power transmission and a core subject we cover every issue. But when it's the focus, we like to attack the subject from multiple different angles.

To start things off, Timken shares with us how they're using the latest software and analysis tools to design and manufacture quieter running bearings that address the modern NVH requirements of diverse applications like wind turbines, automobiles and paper manufacturing equipment (page 22).

Meanwhile, Schaeffler has unveiled their new end-to-end solution for monitoring bearings and other power transmission equipment. OPTIME is their wireless, battery-powered system that can measure temperature and vibration for condition monitoring across a whole plant (page 30).

And don't miss our *Engineering Showcase* special advertising section where leading bearing manufacturers describe their latest technologies and developments (page 26).

Lastly, there's plenty of new bearings-related information online, including our interview with Artur Rdzanek, global product manager for sensored products at ABB. Rdzanek describes the latest developments in ABB's condition monitoring system for bearings (*www.powertransmission.com*). Read it online at *www.powertransmission.com/blog/*.

Other highlights this issue include our technical coverage of motor design. Don Labriola continues his series on hybrid step motors with an article that describes the techniques for measuring various motor parameters (page 54). And Clyde Hancock gives us a detailed FEA and design analysis of various configurations of coreless motors in his article, beginning on page 48.

Lastly, we couldn't claim comprehensive coverage of the power transmission space without excellent articles on gears. We're extremely grateful to our contributors at FZG for their paper on the condition monitoring of gear drives and the difficulties of obtaining consistent data sources to produce reliable, predictive results.

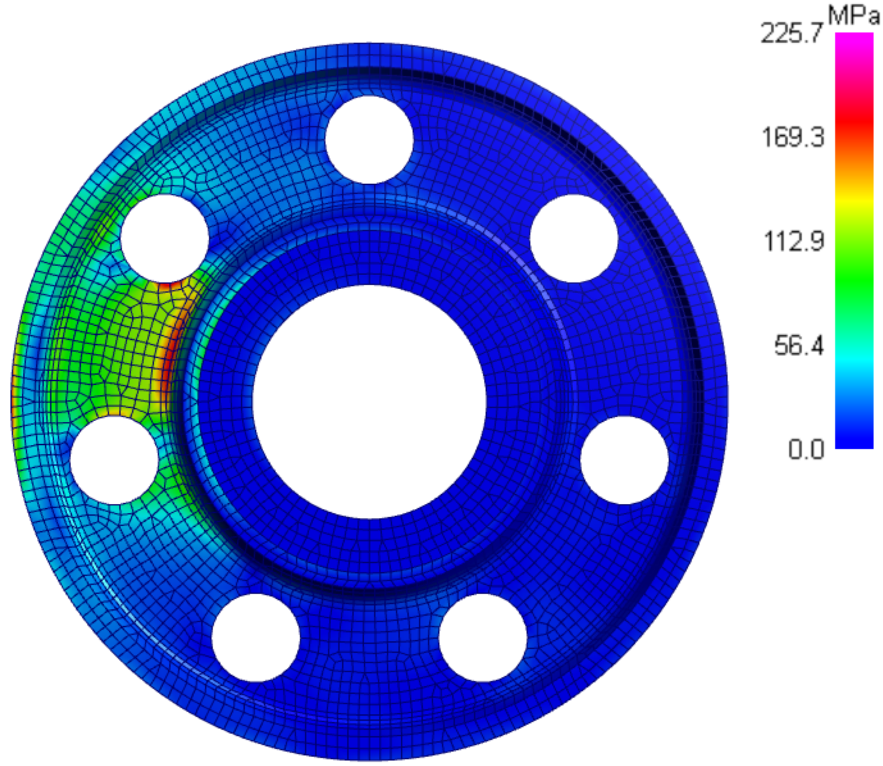
Also on the gear front, Senior Editor Matt Jaster has presented an overview of many of the excellent ways you can still offer your staff training in gear and gear drive technology, even in this era of travel restrictions and social distancing. His article, "Help Wanted," begins on page 38.

We strive to cover as much as possible each issue, so that no matter how you're involved with power transmission components, you'll find something that's interesting and useful.

Thanks for reading.

MESYS

INTRODUCES SOFTWARE VERSION 07/2020



A new version of the *MESYS* shaft and rolling bearing analysis software including new functionality is available. The bearing analysis software allows the calculation of the load distribution within the bearing and bearing life according ISO/TS 16281, and it is integrated in a shaft system calculation with additional possibilities like modal analysis, strength calculation for shafts and interfaces to gear calculations. Currently the software is used by customers in 26 countries on four continents.

General Extensions

The COM-Interface allows easier usage with Python as additional methods were added. Several new methods were added allowing easier access to elements in the shaft calculation.

As CHM-files for help cannot be used over network connections, a new help viewer was added, which can be activated using helpFormat=EXE in 'mesys.ini'.

Calculations with large load spectra or 3D-elastic parts, which take a long time, can now be cancelled using a button in the status bar.

Turkish was already added as an additional language in an update for version 07/2019.

Extensions in the Bearing Calculation

The bearing databases containing catalog data from Schaeffler (FAG, INA) and SKF are updated. The inner bearing geometry is approximated by the software for these databases.

The database including inner geometry by HQW was updated and now also includes bearings from Barden (UK). The database now contains spindle bearings with diameter 3 to 80 mm and several double-row axial angular contact bearings. In addition, a database for spindle bearings from CSC was added which contains internal geometry and diameters from 10 to 160 mm. Further databases from GMN and IBC are available on request from the manufacturer.

The list for bearing tolerances was extended. Now tolerances like 'FAG P4S-K5', 'SKF VQ253', 'GMN UP+', 'HQW X11' can be selected for spindle bearings.

Profiles for rollers and races can now be defined using equations.

A diagram for reliability of a single bearing was added to the bearing calculation like what has been available in the shaft calculation for several versions. A 2D-graphic for orthogonal shear stresses was added.

Using a new custom input for the position in the tolerance field, the parameter variation allows to show results using different positions in the tolerance field.

Extensions in the Shaft Calculation

In this shaft calculation the geometry import as STEP is now possible in case of several parts in one file. Gaps or undercut in the geometry in STEP or DXF-Import can be eliminated by selecting the lines and pressing the key 'c'.

The REXS-Interface is updated to version 1.2. For planetary gear stages still only the import is supported, no export.

An interface to the online SKF Bearing Module was added. This adds two results for bearing life and frictional torque to the results. The SKF-Bearing life is using aSKF instead of aISO and is usually larger compared to Lnmh according to ISO 281.

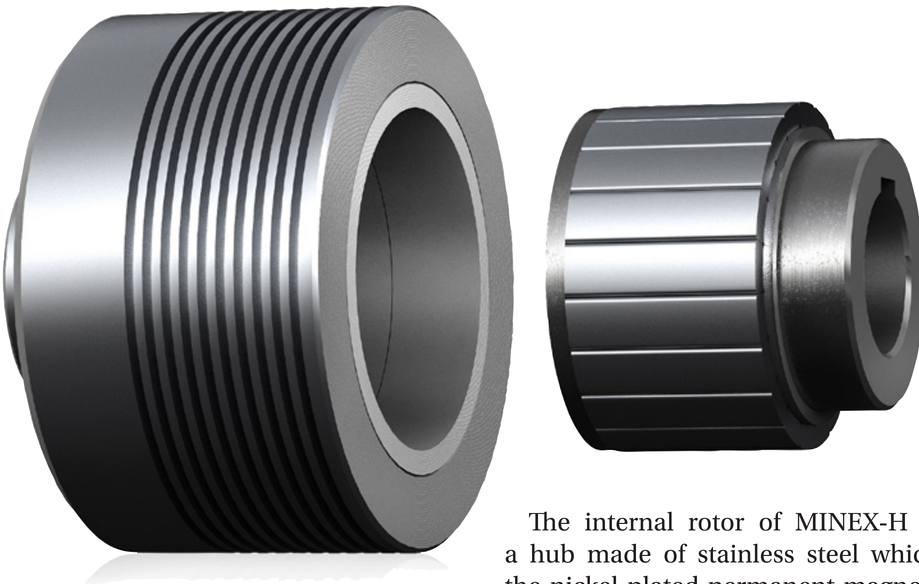
For gear connections an interface to Hexagon ZAR3, ZAR5, ZAR6 for worm gears, planetary gear stages and bevel gears was added. Before only the interface to Hexagon ZAR1 for cylindrical gear pairs was available. For bevel gears a data exchange with KiMOS was added.

For 3D-elastic parts an orthotropic material can be defined for shafts now, and an evaluation of surface stresses has been added. On geometry import as mesh, multiple materials can be used for one part. Additional possibilities for contact between two 3D-elastic shafts have been added. Now displacements, tilting angles and reaction forces are reported for all condensation points. For geometry import as STEP, a preview dialog was added, allowing deleting or merging of parts or remeshing with different settings.

For more information:
MESYS AG
info@mesys.ch
www.mesys.ch

KTR

INTRODUCES HYSTERESIS COUPLING WITH WEAR-FREE OVERLOAD PROTECTION



KTR developed a coupling that transmits the torque contactless via magnetic forces limiting the torque free from wear in case of overload; in addition, the coupling can be applied as a brake. The hysteresis coupling MINEX-H is currently available in three sizes for overload torques from 1.2 to 6 Nm.

MINEX-H is a permanent-magnetic hysteresis coupling transmitting the torque synchronously and contactless between the internal and external rotor via magnetic forces.

The particular feature of this new product is the integrated overload protection: When the operating torque exceeds the selected torque, the coupling slips while ensuring wear-free torque limitation. This process generates a relative speed between driving and driven side while the polarity of the hysteresis material is continuously reversed, and the material is heated up. The holding torque remains almost constant with overload yet may lightly increase with a rising relative speed and the eddy current effects related thereto.

Apart from that the coupling can be applied as a brake in permanent slipping operation. In this case one rotor side is fixed while the other rotor side limits the tensile force set.

The internal rotor of MINEX-H is a hub made of stainless steel which the nickel-plated permanent magnets are arranged on. The external rotor is made up of an aluminum body that the hysteresis rings are located on. The new series is currently available in three sizes for overload torques from 1.2 to 6 Nm with a maximum speed of 1,800 rpm.

Main fields of application of the hysteresis coupling are low speed applications with frequent or permanent slipping; these include, inter alia, filling plants, winding, and unwinding plants as well as medical and materials handling technology.

For more information:
KTR Corporation
Phone: (219) 872-9100
www.ktr.com/us

Michell Bearings

IMPROVES HYDROPOWER STATION WITH THRUST BEARING CONVERSION

Michell Bearings has completed a PTFE conversion of white metal thrust pads at a hydroelectric power plant in Tennessee.

Constructed in the mid-1930s, the Norris Dam was the first major project for the Tennessee Valley Authority (TVA). Its purpose was to bring economic development to the region and control the flooding that had long plagued the Valley.

TVA worked with Michell Bearings after experiencing numerous thrust bearing failures over the life of one of the two generator units. The failures of the original white metal bearings

resulted in excessive downtime and associated loss of revenue.

Michell Bearings was awarded a design contract to investigate the potential problems with the 1930s design, which had been subject to various attempts over the years to improve reliability. The engineers at Michell Bearings created a 3D model of the thrust bearing support structure and performed a finite element analysis to determine any issues affecting the bearing's performance.

Michell Bearings' in-house performance prediction software was used to evaluate the performance of the existing white metal pads.

The bearing's thrust pads were replaced using a PTFE-lined alternative as a result of the study. The PTFE material provides a greater safety factor when compared with the white metal solution. PTFE is more durable and has a well-established and proven track record within the hydro power sector. The study concluded that the material will also increase the life of the bearing and provide greater reliability.

Steve Dixon, CEO at Michell Bearings, said: "Although the original contract was awarded as a study, we were pleased to hear that our advice was taken on board and led to the supply of the PTFE thrust pads for the Norris unit."

Previously engineering director at Michell Bearings, Dixon took on the role of CEO in May 2020. "We have been researching the advantages of PTFE for over 20 years and so we were confident that the material would solve TVA's problem."

Michell Bearings and TVA are working on an additional two projects at the Cherokee and Douglas hydropower plants. Michell Bearings will be presenting a paper on the findings of this project at the Hydrovision exhibition in June 2021.

For more information:

Michell Bearings
Phone: (267) 822-0704
www.michellbearings.com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Rollon

PRESENTS REDESIGNED PRODUCT LINE

Rollon has introduced its new Compact Rail on the market, now with a Plus version, in addition to the new actuators from the Plus System and Smart System families. These products are the first of a comprehensive technological and aesthetic redesign program that will progressively affect the entire product range. Increased performance and attention to detail to satisfy the needs of manufacturing companies are the main priorities, and now Rollon wants to add functional and original aesthetics.

The first lines to benefit from the new design are the Compact Rail products and, from the actuator catalog, the ELM and ROBOT products from the Plus System family and the corresponding E-SMART and R-SMART from the Smart System range. All these products have been technologically and aesthetically renewed. Their appearance was modified to increase performance and opportunities for industrial designers — with regard to production, procedural and economic efficiency — and to offer pleasant looking products that can be integrated perfectly into the factory design.

For Compact Rail, the system of rails with bearings in cold drawn steel with induction hardened and ground raceways whose main strength is being able to manage misalignment, Rollon has introduced a new version that offers great reliability in dirty environments and resistance to corrosion (they can be treated with Rollon Alloy — passivated electro-galvanization — or nickel-plating or galvanizing ISO 2081). The new Compact Rail also enjoys a long lifespan due to the induction hardened raceways, high performance, solidity and sturdiness guaranteed by the steel slider, and many other features that allow this product to be used in different types of applications.

The new Plus version also guarantees higher performance levels, thanks to the double ball bearings and new rails with convex raceways, which guarantee greater rigidity with increased load capacities up to +170% in the axial direction and +65% in the radial direction. Lastly, the entire Compact Rail range, in its renewed version, offers new steel sliders equipped with self-centering raceway cleaners, integrated lubrication systems for the raceway cleaners with a slow-release felt pad for automatic lubrication, lateral seals to protect the internal components and a cover on top to prevent accidental alterations or tampering with the radial ball bearing rollers.

Regarding the actuators, the technological innovation and design process concerns the ELM and ROBOT products from the Plus System family and the corresponding E-SMART and R-SMART from the Smart System range.

Regarding the Plus System family — or rather, the protected linear actuators


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REGAL®

with anodized aluminum profiles, self-sustaining structures and toothed belt transmissions — the main changes concern the introduction of heads with hollow shafts instead of protruding shafts to connect with the locking assembly and reduction gear. Thanks to these new features, the gear motor can be mounted on the actuator directly by the client, a considerable improvement in terms of time, procedures and cost, for the clients themselves, and a substantial reduction in time to market. Therefore, our clients can now remove the cover belt without our intervention, thanks to the quick release of the block integrated into the flange that connects the profile and the actuator head.

Aesthetically speaking, Plus System products now have a blue finish and radiated heads, instead of squarish heads. The Rollon logo placed on the heads looks like the raceway cleaner head on the new Compact Rail. An updated version of the carriage has also been introduced, with heads on both sides.

The new features introduced in the Plus System product family are also present in the Smart System range, a family of linear actuators closely connected with the Plus family, which offer a very convenient price-quality ratio, high performance and a very simple and precise construction. Products from the Smart line now have a black transmission belt and new carriages. These also have radiated heads, with a groove that gives a sense of continuity to the line formed by the transmission belt.

For more information:
Rollon by Timken
Phone: (973) 300-5492
www.rollon.com

FVA GmbH

RELEASES WORKBENCH 6.0

FVA GmbH has released the latest version of its simulation platform for drive systems. The software combines innovative, research-based calculation methods with user-friendly presentation of results.

With the *FVA-Workbench 6.0*, released on July 28, 2020, mechanical and hydraulic systems can be optimized, the precision of analyses increased, and development processes made more efficient.

Key features include: scientifically proven calculations — high precision thanks to validated methods based on the current state of research; scalable levels of detail — precise analysis of individual gearbox elements through to comprehensive system calculations; maximized efficiency — easy-to-understand graphical reports for fast and accurate interpretation of results.

The new *FVA-Workbench* calculation methods were developed and validated in the Forschungsvereinigung Antriebstechnik e.V. (FVA, The Research Association for Drive Technology), the largest drive technology research and innovation network. Through member contributions and public funding, the FVA generates 17 million euros annually in research projects at leading research institutions. The *FVA-Workbench* serves as a platform for the practical and efficient application of knowledge gained in FVA research projects.

For more information:
FVA GmbH
Phone: +49 69 6603-1663
www.fva-service.de/en

NORD

RELEASES HOLLOW SOCKET SHAFT DESIGN FOR GEAR UNITS

NORD DRIVESYSTEMS introduces a new hollow socket shaft design for NORDBLOC.1 single-reduction gear units. This shaft design mounts directly to a pump without the need for couplings, significantly reducing installation time and maintenance, greatly extending the operating life of the unit, and drastically reducing revenue loss as a result of unexpected downtime.

Couplings have always been a challenge, and they are a common failure point within drive systems. Keeping shafts aligned not only eliminates vibrations, but also prevents additional load and wear-and-tear on drive units. Unfortunately, this is easier said than done, as even the most seasoned technicians are required to adjust and shim, sometimes for hours, to get as close to perfect alignment as possible, knowing that even the slightest misalignment will ultimately shorten the lifecycle of the gear unit.

NORD initially approached PSG, a Dover company, with the idea of a coupling-free system for their Blackmer Series pumps. After many months of collaboration, the design was finalized for a hollow socket shaft for Blackmer's GNX and GNXH products. The new turnkey design reduced the time and costs of integrating new units to almost zero, making it a preferred pump solution that earned PSG a net revenue improvement of 47 percent.

For more information:
NORD
Phone: (888) 314-6673
www.nord.com

THK

CAGED BALL SCREW ENABLES HIGH-SPEED, COMPACT MACHINE DESIGNS

THK's new Type SDA-V/SDAN-V Caged Ball Screw is engineered to enable the development of high-speed, compact machine designs.

Featuring newly developed circulation components, the Type SDA-V/SDAN-V picks up balls in the tangential direction and achieves a maximum rotational speed of 5,000 rpm (DN value of 160,000 max.). Torque remains stable even during long periods of high-speed operation. Type SDA-V/SDAN-V nut dimensions conform to DIN standards (DIN69051-5).

The Type SDA-V Caged Ball Screw is ideal for a wide range of applications, from small electronic component machinery to large general industrial. Fifty-nine products are available with a combination of shaft diameters from ø12 to ø50 and leads from 4 mm to 50 mm. Clearance can be selected, including an axial clearance of 0 or less.

The Type SDAN-V Caged Ball Screw is designed with higher axial rigidity than the Type SDA-V. It is suitable for use with NC machine tools and precision equipment when is it necessary to minimize displacement from the force of cutting. Shaft diameters range from ø31 to ø50 and leads from 10 mm to 20 mm. A double nut is used to achieve axial clearance of 0 or less. Full-ball versions are available for both the Type SDA-V and the Type SDAN-V.

The Type SDA-V/SDAN-V features patented THK Caged Technology for smooth and quiet motion. Caged Technology employs a synthetic resin cage with a patented curvature that cradles each ball and separates it from the next. The spaces between the rolling elements retain grease and act as a lubrication system for long-term maintenance-free operation. Other Caged Technology benefits include increased speed and accuracy, decreased noise levels, low dust generation and long life.

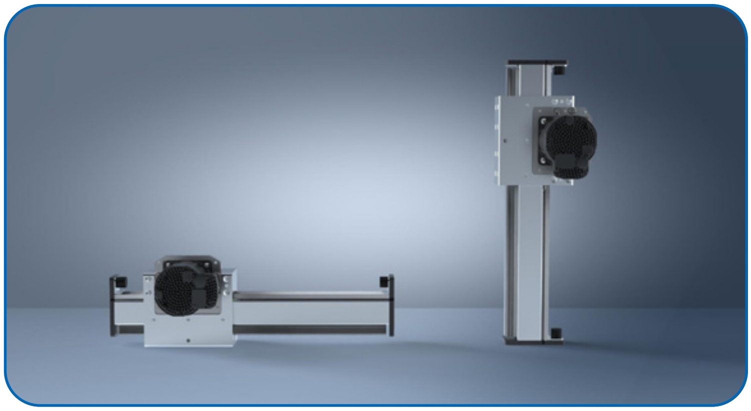
The Type SDA-V/SDAN-V complies with conventional JIS (Japanese Industrial Standards) as well as ISO (international standards) and DIN (German industry standards).

For more information:

THK
Phone: (847) 310-1111
www.thk.com

Bell-Everman

OFFERS HIGH-PERFORMANCE REPLACEMENT ACTUATOR



Bell-Everman has launched ServoBelt RA, a new high-performance, drop-in replacement actuator designed for applications that have traditionally used rod actuators, pneumatic cylinders or even linear motors. Unlike traditional rod actuators, ServoBelt RA is fully guided along theentirety of its stroke, making it more resistant to off-axis loads and more stable in on-axis moves.

With linear forces up to 200 N, speeds up to 4 m/s, accuracy to +/- 4 μm per meter and bi-directional repeatability as low as +/- 25 μm depending on deceleration profile, ServoBelt RA performance compares favorably to linear motors that cost thousands more.

ServoBelt RA has been built from the ground up for moving chassis installation in both horizontal and vertical Z-axis orientations. Its drive unit features standard or custom mounting hole patterns to make it easy to integrate ServoBelt RA into your machines. A range of standard motor offerings enables the replacement of pneumatic cylinders simply by connecting DC power and rerouting servo-valve signals to the ServoBelt RA.

For more information:
Bell-Everman
Phone: (805) 685-1029
www.bell-everman.com

Maxon Motors

RETURN TO MARS

In July, NASA sent its fifth rover to Mars. Its main mission is to collect soil samples that will be analyzed on Earth at a later time. The rover will also carry a helicopter that will perform the first flights on the Red Planet. Maxon's precision DC and BLDC motors will be used for numerous mission-critical tasks.

Maxon drive systems are very familiar with Mars. These drives have been used in virtually every successful robotic mission over the last three decades. There are now more than 100 of them on the Red Planet and there are likely to be more soon. The launch window for NASA's next mission opens on July 22nd. An Atlas V rocket will launch the new Perseverance rover on its way to Mars, where it will be searching for signs of previous life on the planet. Its most important job is to take multiple soil samples, seal them in containers and deposit them on the surface of Mars so that a future mission can return them to Earth. Several Maxon motors will be used to handle the samples inside the rover. For example, Maxon DC motors are installed in the robotic arm, which moves the samples from station to station. Maxon motors will also be used for sealing and depositing the sample containers.

NASA's Jet Propulsion Laboratory (JPL), is carrying out the mission, and have asked Maxon to produce 10 drives for the rover. As with almost all previous Mars missions, these drives are based on standard products from Maxon's catalog with modifications. For the first time, NASA is using brushless DC motors, including: nine EC 32 flat and one EC 20 flat in combination with a GP 22 UP planetary gearhead. Working closely with JPL specialists, Maxon engineers developed the drives over several years and tested them thoroughly to achieve the highest standards of quality. "We've learned a lot from this exciting project," says Robin Phillips, head of the Maxon SpaceLab. "We now have very broad expertise in space applications and have established quality assurance processes that meet the expectations

of the industry. Customers from other industries such as the medical sector, where requirements are often similar, can also benefit from this know-how." Space missions place the highest demands on drive systems. This includes vibrations during the rocket launch, vacuum during the journey, impacts on landing, and the harsh conditions on the surface of Mars, where temperatures fluctuate between -125 and +20 degrees Celsius and dust penetrates everywhere.

The Perseverance rover is expected to land on Mars on February 18, 2021 — but it won't be alone. A drone helicopter called Ingenuity will be attached to the underside of the rover. It weighs 1.8 kilograms, is solar powered and will perform several short flights, as well as take aerial images. The main goal of this experiment is to test the concept for further drones of this kind. Maxon has six brushed DCX motors with a diameter of 10 millimeters controlling the tilt of the rotor blades and the direction of flight. The drives are very light, dynamic and highly energy-efficient. These properties are crucial, because every gram counts on the Mars helicopter. Flying on Mars is not easy. The atmosphere is extremely thin, roughly comparable to the conditions on Earth at an altitude of 30 kilometers. The drone helicopter has flown in a simulated test environment in the JPL laboratory. Whether it will lift off on Mars remains to be seen. First, other obstacles, such as the rocket launch, must be successful.

"We hope that everything goes well and that we'll soon see our drives in action on Mars," says Maxon CEO Eugen Elmiger. "We're all keeping our fingers crossed."

For more information:
Maxon Motors
Phone: (508) 677-0520
www.maxongroup.com

Timken Addresses NVH Requirements in Bearings

Matthew Jaster, Senior Editor

As NVH technology advances, so do the tools that allow engineers to study, test, and manufacture bearings capable of delivering high-performance and quality.


NVH data in the wind industry has led to educational and training opportunities for Timken.
All photos courtesy of Timken.

Everything is subject to variations during the manufacturing process, according to Dr. Desheng (Victor) Li, senior NVH engineering specialist at Timken. The geometry variations, in the form of waviness and surface roughness on ring raceways and rolling element body, are called manufacturing imperfections because all manufactured parts will naturally have some level of variations that cannot be eliminated.

When a bearing rotates, the manufacturing imperfections can excite the bearing to vibrate and radiate sound into its surrounding environment. Compared with the manufacturing imperfections, however, the damage such as dents and spalling on bearing components and lubricant contamination are typically the major sources for most significant bearing noise and vibration in applications.

Timken has developed and applied advanced NVH simulation technology to help make bearings quieter and more precise. The following article will discuss how this technology has evolved in recent years and how it might change in the future to meet the increasing demands in the marketplace.

Application Advantages

"How quiet is the automobile today versus what we deemed was acceptable 10, 15, even 20 years ago?" asked Brian Ray, chief engineer-industrial at Timken. "With the evolution of the electric vehicle, the entire drivetrain (every piece of rotating equipment) needs to be quieter to accommodate today's NVH quality standards."

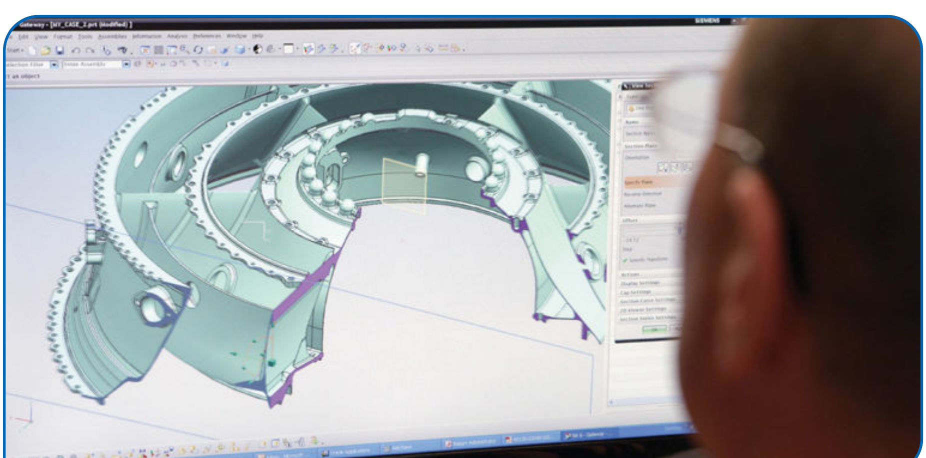
Ray cites the increase in condition monitoring as a significant factor in the growth of NVH tools in 2020. "Engineers are adding more sensors to their equipment while proactively monitoring the signals and the component data. Vibration is typically one of the signals to focus on in condition monitoring," Ray said.

Industries like automotive, paper, and wind have led the way in recent years allowing engineers to examine bearings in diverse applications and environments. Ray said that the NVH data in these areas has led to educational and training opportunities and prepared Timken to better understand how to keep bearings running at the highest and most efficient levels.

"Vibration needs to be considered for all machine tools—whether it's a grinding, milling, or drilling process—in order to create tighter part tolerances," Li added.

The changing requirements in the automotive industry will lead to new NVH tools and resources as more hybrid and electric drivetrains replace the internal combustion engine.

"In many cases, customers are concerned about noise-causing vibration that could lead to performance challenges in the larger system," said Li.


CAD view of a bearing.

> "The challenge is to design bearings that not only meet performance requirements, but also can be manufactured with a competitive cost," said Dr. Desheng (Victor) Li, senior NVH engineering specialist at Timken."

The vibration of rotating equipment can also impact the performance and appearance of the finished product as well.

"Another example is the flat rolling of products in the metals industry. Any variation or vibration of the rotating rolls can translate into the finish rolled product, making it visually unacceptable. Applications like automotive body panels and appliances are sensitive to surface variations. Timken has helped our cold-mill customers to solve mill chatter issues so that they can produce aluminum sheets qualified for automotive applications," Li added.

Bearing NVH Research

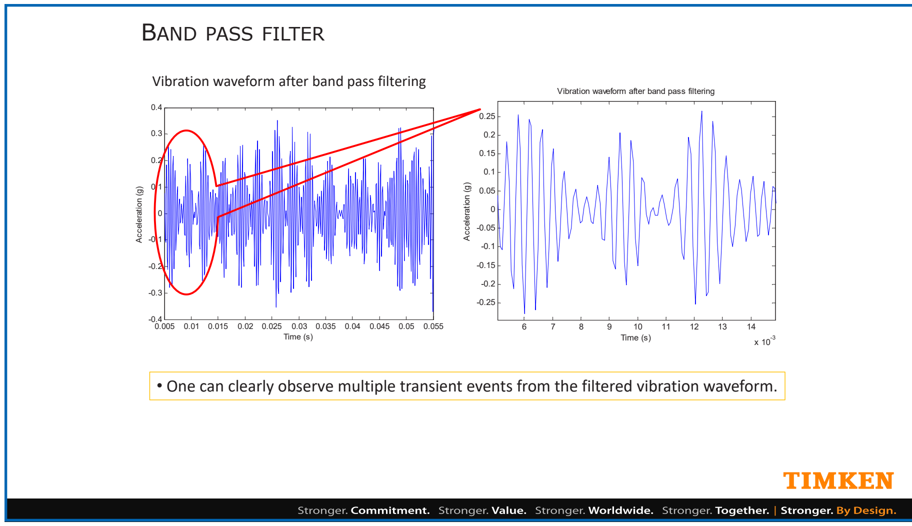
There are four major driving forces behind NVH research. The first one is the increasing demand for quiet products, such as passenger cars and home appliances, from consumers; the second one is that vibration can affect the quality of the product produced by a machine such as machine tools and cold mill stands; the third one is the tightening government regulations on environmental and workplace sound levels; the fourth one is that some customers use bearing sound and vibration as an indicator of bearing quality and life.

Although noise and vibration can be an indicator for bearing damage, there is no solid scientific evidence yet to support the correlation between the sound and vibration generated by typical manufacturing imperfections and bearing life.

"The challenge is to design bearings that not only meet performance requirements, but also can be manufactured with a competitive cost," Li said.

Without simulation software, engineers are forced to go through multiple iterations by making the physical prototypes, putting them on a test rig, and measuring the NVH. The process lengthens product development time and increases cost.

"Historically, I would say physical testing has been the benchmark and industry standard for measuring and trying to improve the NVH performance of bearings," Ray said. "In order to prove the performance increase, you have to physically test the bearing and then review the data with your customer."



Bearing damage diagnosis using envelope analysis.

Recent innovations on the mathematical and modeling side have changed things.

"The vibration of a multibody system is extremely complex, so it's difficult to model and takes a lot of 'computer horsepower.' In recent years, we've seen great improvements in analysis software and NVH performance can now be simulated in some industries virtually," Ray said.

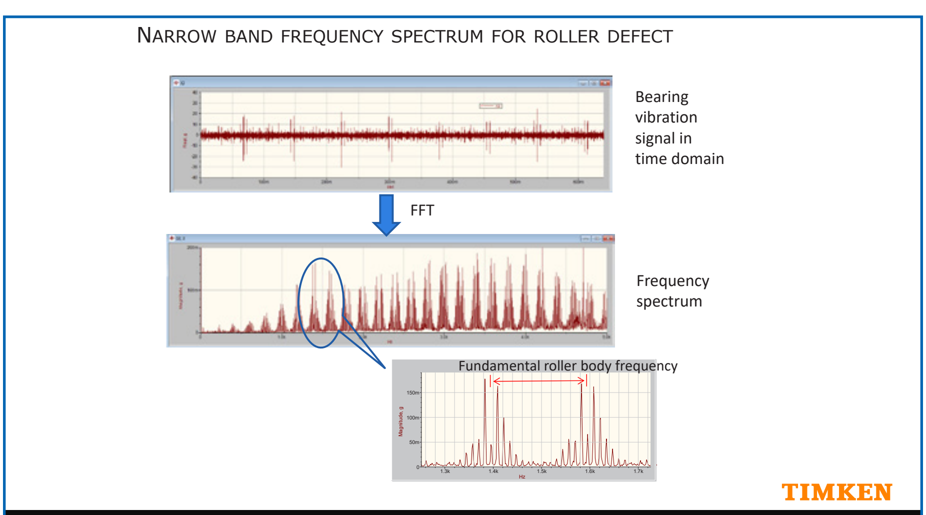
The Virtual Sound Test System

Even with the significant improvement in commercial simulation software and computer power, it is still a big challenge to conduct bearing NVH simulation because thousands of contacts need to be simulated when a bearing rotates. It could take days to conduct one simulation if a FEA or multibody dynamic commercial software is used. To tackle this challenge, Li developed Timken's proprietary bearing NVH simulation software called *VSTS (Virtual Sound Test System)*. Thanks to its sophisticated algorithm, *VSTS* runs much faster than the commercial software, making it feasible to be used as a design tool.

"This software tool takes the whole system into account," Li said. "It can predict the system-level vibration not just of the bearing. The system dynamics of a gearbox, for example, may amplify the bearing vibration at system natural resonance frequencies, so it's extremely important to include system dynamic properties in the simulation."

In addition, *VSTS* allows Timken engineers to work with OEM designers at the earliest stages of product development. "We can simulate all of the design features of a bearing," said Li, "rotating at different speeds or under different load conditions. We can simulate conditions with outer ring rotating or inner ring rotating."

Modeling can also be used to simulate damage that may occur in service. *VSTS* has been thoroughly validated with test results. Li used measured waviness, surface roughness, and dent size as input in *VSTS* for simulations. He then measured the vibration of the bearings and used the test data to validate *VSTS*.



Narrow band frequency analysis.

One of the successful applications of *VSTS* was to develop manufacturing specifications for a customer application. One customer had requested strict specifications for every bearing component—from the inner and outer rings to the individual rollers. The Timken sales and customer engineering teams worked with R&D to run *VSTS* simulations for the scenarios that the customer was designing for. They presented the resulting data as proof that Timken's proposed alternative specifications would have the same or better NVH performance than the one the customer had originally requested without as many tolerance restrictions.

In addition to the advanced simulation capability, Timken's sound test equipment is capable of testing bearings of various size from small automotive to larger industrial bearings, and of various types from tapered, cylindrical, and spherical roller bearings to ball bearings.

Furthermore, the NVH Lab has portable sound and vibration measurement equipment which can be brought to customers' site for on-site measurement and analysis to identify where noise and vibration are coming from.

"We've come a long way in both simulation and testing technologies," Li said.

Artificial Intelligence and the Future of NVH Analysis

In the not-so-distant-future, Li believes the time will come when VR can be utilized in the computer simulation. "I see virtual reality as another tool for product development," Li said. "Bringing the customer into a virtual environment and letting them hear the sound and feel the vibration that a bearing makes in a system would be really impressive and more intuitive than a bunch of data and charts."

Another growing area is artificial intelligence (AI). Ray said that NVH today is a manual process where a piece of equipment collects vibration measurements and then engineers take this data, troubleshoot the problems, and come up with potential solutions.

"Basically, the condition monitoring system examines a signal to determine if things are running smoothly. You may get a green light if everything is working properly or a red light if something is wrong. This is where we're at in 2020," Ray said.

In the future, Ray believes AI will become advanced to the point where the machine itself will examine the data, identify problems, and fix these issues automatically.

"We're already seeing a pull in this direction across manufacturing," Ray said. "We may soon get to a point where the machine will interpret and identify bearing issues without any human interaction whatsoever." **PTE**

> "How quiet is the automobile today versus what we deemed was acceptable 10, 15, even 20 years ago?" asked Brian Ray, chief engineer-industrial at Timken. "With the evolution of the electric vehicle, the entire drivetrain (every piece of rotating equipment) needs to be quieter to accommodate today's NVH quality standards."

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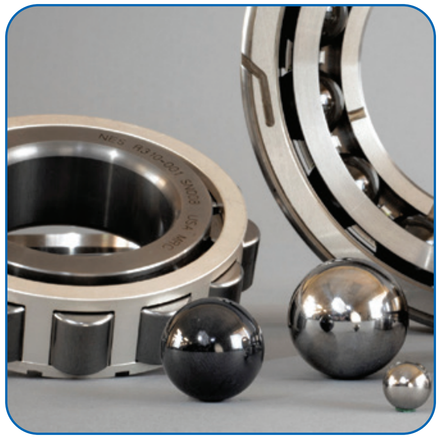

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Schaeffler

Readies Launch of End-to-End Wireless Sensor Solution with OPTIME

Matthew Jaster, Senior Editor

Schaeffler has more than 134 years of experience manufacturing bearings under the FAG, INA and LUK product brands. For years, the company has offered scalable condition monitoring systems tailored to meet the specific requirements of each end user. *PTE* recently caught up with Schaeffler Manager of Condition Monitoring-Americas, Frank Mignano, to discuss the evolution of condition monitoring for bearings and the upcoming introduction of their next-generation condition monitoring platform called OPTIME — a cost effective, IIoT-focused end-to-end wireless sensor solution with cloud computing analytics.

Building on Bearing Knowledge

As a solutions provider, Mignano said that Schaeffler's goal is to be able to handle any application in the most efficient way possible, while providing the most value to the end user. Schaeffler's condition monitoring systems are designed to be scalable, depending on the specific end user's requirements.

"This means we can monitor a few bearings or many bearings in a facility — or anything in between — because expanding our systems is easy. While multichannel solutions like Schaeffler's ProLink system can handle a cluster of critical bearings on a drive system gearbox, for example, OPTIME can handle the remainder of the balance of plant rotating assets in a facility," Mignano said.

Over the years, condition monitoring systems have moved toward smaller, less expensive designs that are more tightly integrated with end user facilities, while maintaining a clear focus on IIoT and the advantages offered by cloud computing.

"Integration is achieved by sharing speed and load data from existing site systems, while also sending vibration and temperature data to existing plant assets such as a PLC or DCS system. Another challenge for any company in the condition monitoring business is to interpret the complex vibration data and turn it into actionable information for the end user," he added.

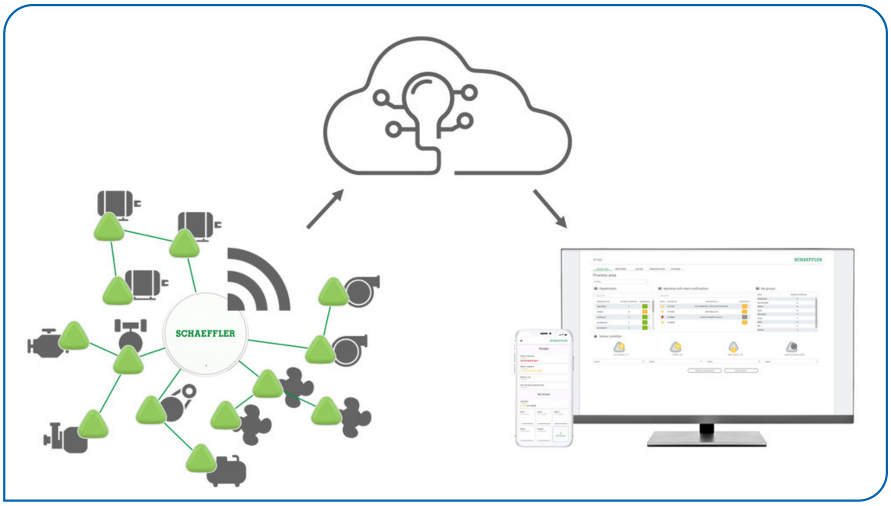
Mignano said that Schaeffler has accomplished these objectives with OPTIME.

For example, using advanced, proprietary algorithms, Schaeffler can combine data such as acceleration, demodulation, and kurtosis into actionable information for the end user.

"Our artificial intelligence algorithms enable us to determine (in this example) whether all three variables are elevated and, additionally, whether bearing frequency peaks are present in the demodulation or acceleration spectrum data. This would indicate that the bearing being monitored is

The Schaeffler OPTIME ecosystem. All photos courtesy of Schaeffler.

in a critical state and needs to be changed within the next two months. Much of our work has been focused on taking the mystery out of vibration analysis, while creating a tool that can easily provide maintenance planning help for the end user," Mignano said.



Smartphone-compatible: OPTIME's data is easily accessible and configurable.

What is OPTIME?

According to Mignano, OPTIME is a fully wireless, battery-powered vibration and temperature monitoring system designed to be deployed on all balance of plant assets in a manufacturing facility. (In a large paper mill, for example, an OPTIME system could encompass 2,500 sensors deployed throughout the site. A smaller cement mill, on the other hand, might require 500 sensors.) Each OPTIME sensor is designed to last five years, and it will store seven sets of overall data every four hours — plus a Time Waveform/FFT once per day.

"OPTIME communicates via a self-healing MESH network to a cellular gateway — each of which can process up to 70 sensors — that sends the data to the Schaeffler Cloud, where advanced analytics are performed. The actionable information is then available on a smartphone app (available for iOS and Android) as well as on the Schaeffler Cloud. Cost-effectiveness and ease-of-use were two of the main targets that were clearly met during the design and implementation of the technology," he added.

Condition Monitoring Evolution

The technology to be able to detect rotating equipment and specifically bearing defects so that maintenance can be identified, planned, and executed at minimal cost has existed for years.

"This is the goal of portable as well as installed Predictive Maintenance (PdM) technologies. Each has its own unique challenges: An installed system is not only (relatively) expensive to purchase, but also expensive and time-consuming to install and maintain over the years. Portable vibration systems, meanwhile, are very effective, but they are manpower-dependent and time-based. This means that certain failures can occur between regular collection intervals," Mignano said.

IIoT has advanced sensor technology into a fit and form factor that makes it cost effective to monitor the customer's entire array of rotating assets online, thereby reducing Total Cost of Ownership (TCO) and enabling data and information to be available on each asset and for all pertinent employees — 24/7.

A "smart" bearing can tell you when it needs to be re-lubricated or if it is failing and needs to be replaced.

"Instead of suffering a bearing failing without warning during a critical production run, technologies such as OPTIME — with its ability to provide over 1,200 data points per sensor per month — can give you advance warning when bearing conditions change. Then it simply becomes a matter of planning the repair during a normal maintenance outage, when personnel are available, and parts have been ordered. The goal of a smart bearing is to minimize interruptions to production schedules," Mignano said.

Technologies like ProLink and OPTIME — and even Schaeffler's innovative Concept1 automatic lubricator — are more critical than ever during the coronavirus pandemic, as many employees are not able to make it to the factory to perform normal maintenance checks or re-lubricate bearings. This is where automation takes over. This scenario is particularly prominent in the food and beverage industry where less human contact is practically required.

Tools like OPTIME are a cost-effective and easy-to-deploy solution to a) automate the required data collection and b) utilize years of experience embedded into the device's advanced algorithms to provide actionable information about the condition of all of the bearings inside a facility's rotating assets. Moreover, automatic lubricators such Schaeffler's Concept1 can ensure clean lubrication is automatically supplied at the proper intervals.

Bearing Healthcare—Next Steps

Mignano believes the next step after OPTIME technology would be to provide bearings with sensors -embedded into or adjacent to the raceways — that capture critical bearing health information such as vibration, temperature, load, speed and lubrication condition, and then make this data available to the end user as actionable information.

"The ultimate solution would be to implement monitoring tools that would enable a simple, easy to read and reliable "Bearing Health Dashboard" (kind of like your car's fuel gauge) that would indicate how much life is left in the bearing — is it full or closer to empty?"

OPTIME is set to officially launch in the United States in January 2021. **PTE**

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The Maintenance of High Quality and Taste

Valves help control temperature, pressure and viscosity for alcohol fermentation

Amit Patel, Product Market Manager, Emerson

The alcohol business is booming. The explosion of craft beers, demand for new wine blends and rise of international distilleries mean consumers now have more choices than ever. No matter the size, beverage manufacturers need to make sure their products maintain the same high levels of quality and taste.

The fermentation process in the beverage industry requires precise temperature control.

The key lies in the fermentation process, which requires precise temperature control to ensure quality, consistency and taste across various beverage styles and flavors. Optimum temperature control requires the right valve system to control heating and/or cooling parameters.

Alcoholic beverage producers typically control tank temperatures using glycol or ammonia systems. This nontoxic liquid media flows through thermal jackets surrounding the fermentation tanks. In a closed circuit, the glycol is pumped through a chiller, where it is cooled, and then flows back down through the jackets — cooling the tanks and their contents. Not only does temperature affect the speed of the fermentation process, but it also affects the taste and quality of the final beverage.

Because fermentation is such a vital process, it's no surprise beverage-makers increasingly are looking to install or upgrade their tank cooling and heating systems. But these modifications don't come cheap, nor without challenges. Many facilities, particularly smaller operations, have limited physical space. As a result, tank systems need to be positioned as close as possible to each other to maximize floor space and remain accessible during maintenance. The following are other challenges to consider:

- The high cost of energy: Energy is one of the largest overhead costs in the food and beverage industry. Because fermentation is considered a wet environment, beverage-makers also need to have additional electrical safety features in place.
- Lengthy piping processes: The labor required for piping and wiring can be costly and very time- consuming.
- Potentially unreliable yields: For wineries, in particular, any issues that compromise batches during extended fermentation periods equate to several years' worth of lost time, materials and cost.

In addition to ensuring precise temperature control, proper valve selection can address the challenges associated with installing, maintaining and upgrading fermentation heating and cooling systems.

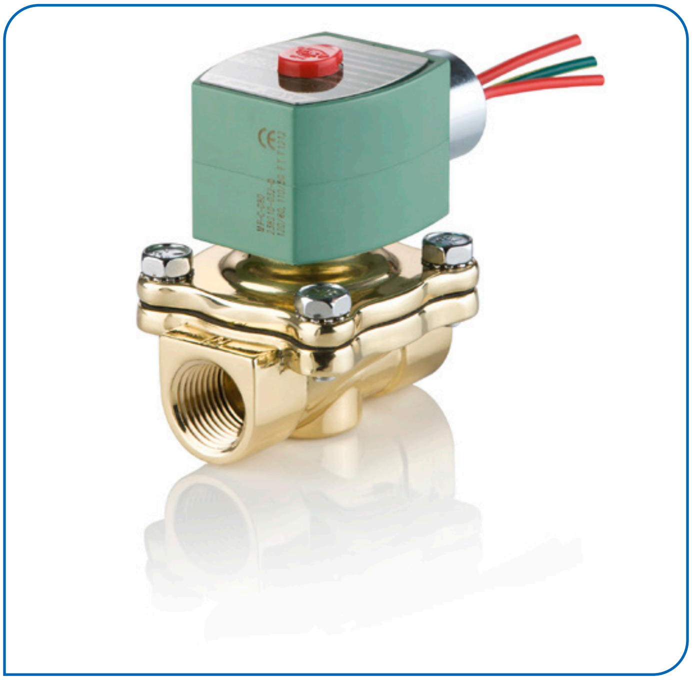
Depending on the system, it also is important to select valves that are rated to handle glycol or ammonia.

Suppliers like Emerson can help an operation select the right fluid automation product to meet one's individual needs.

Choose from the following valve solutions, all of which are suitable for systems using glycol or ammonia:

Two-way valves: Two-way valves are a traditional valve type for fermentation heating and cooling systems. The high-flow solenoid valves come in a range of pressure ratings, sizes and resilient materials like brass or stainless steel, providing long service life and low internal leakage.

NEMA washdown solutions eliminate contamination and protect components from corrosion that may cause downtime.



High-flow solenoid valves, such as the ASCO Series 8210 provide long service life and low internal leakage in heating and cooling systems.

The ASCO Series 290 is a pressure-operated, direct acting angle-body piston valve built for demanding applications such as fermentation.

Next-Gen valves: Next-Generation solenoid valves include several electrical enhancements designed for greater energy savings and a longer service life. Look for valves that incorporate power management circuits, as well as electrical surge suppression to both the solenoid and electronic controls.

Because the valve's DC characteristics now rival AC pressure and flow values, manufacturers can eliminate AC output cards to simplify control, reduce wiring costs and provide safer working environments for DC users.

Angle body valves: Air-operated, direct-acting angle body valves are ideal for aggressive and high-viscosity fluids. Many models feature a straight-through design and wide range of advanced options, including a signaling box, compact positioner for proportional control and stroke limiter. They allow tight shutoff in both directions and contain no bleed holes — eliminating the chance of glycol plugging.

Six-port valves: Comprised of two actuators, six-port valves provide the benefits of the traditional angle seat valve in a single body design. Manufacturers can use one valve body to control hot and cold glycol supply and return flows, which reduces installation time.

In addition to proper valve selection, it's important to consider automating your fermentation heating and cooling systems to achieve even greater thermal precision. For example, the G3 Electronic Fieldbus Platform makes this process quick, simple and painless. G3 integrates communication interfaces and input/output (I/O) capabilities into your pneumatic valve manifolds — allowing your PLC to more efficiently turn valves on and off. **PTE**

For more information:

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Amit Patel is a product marketing manager at Emerson. He focuses specifically on the food and beverage market for the Americas world area. He earned his bachelor of science degree in electrical engineering from the New Jersey Institute of Technology, and holds a Six Sigma Black Belt.

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Help Wanted

Options available for those looking for safe, online/in-person gear knowledge

Matthew Jaster, Senior Editor

By the end of the year many of us can add "Zoom Proficient" to our LinkedIn profiles. Obviously, we're all doing the best we can under these unusual circumstances—despite more kids and dogs showing up in the middle of these meetings. Still, the show must go on during the pandemic, gear companies need skilled workers (now more than ever) and these skilled workers need the right training and educational tools to broaden their areas of expertise.

Our resident blogger Charles D. Schultz gets frequent calls asking if he knows someone ready to move up. "That is a very inefficient query; many people feel they are due a promotion. Not all of them have the skill set needed by the inquirer. Others have geographical limitations or "defects" in their resumes that disqualify them for the typical "help wanted" ad," Schultz said in a recent blog entry (*www.geartechnology.com/blog/finding-good-candidates/*).

"My standard reply is 'Why not promote someone who already works for you?' Some of my best *hires* were machine operators who asked lots of questions and frequently drove their supervisors or my staff crazy. Sound like someone you know? Yes, they were rough around the edges and lacked the "book learning" needed to move into the office. But none of the five or six who were brought in from the shop ever let me down. Sure, they required training, but they understood our system and were determined to succeed."

Gear drive and gearbox knowledge is at an all-time premium in 2020. Manufacturing—like most other industries—is currently experiencing a roller coaster of economic uncertainty. It is best to keep the employees you value the most engaged, motivated, and continuously learning. Here's a few upcoming online/in-person courses to consider:

Raymond Drago teaches both the AGMA Gearbox Systems Design and Detailed Gear Design courses.

AGMA Gearbox Systems Design

This course, taught online by Raymond Drago and Steve Cymbala, focuses the supporting elements of a gearbox that allow gears and bearings to do their jobs most efficiently. Attendees learn about seals, lubrication, lubricants, housings, breathers, and other details that go into designing gearbox systems. They learn about the types of housing construction and housing elements, apply drawing practices, learn more on bearing mounting, retention, and sealing and understand the role of gearbox accessories. Attendees will also learn about lubricant selection, application, and chemistry. This live, virtual online training course (2 CEUs) takes place October 13–15, 2020. Register by September 29 here: *www.agma.org/education/online/video-training/gearbox-system-design/*.

AGMA Detailed Gear Design—Beyond Simple Service Factors

Through support from the AGMA Foundation, the Detailed Gear Design live course is available pre-recorded, online for wider availability. Taught by gear expert, Ray Drago, P.E., of Drive Systems Technology, Inc. Students can get the full experience of the course through 15 one-hour segments and supporting training documents. Detailed Gear Design (2 CEUs) teaches students about gear design and then walks students through carefully crafted "problems" that will demonstrate the practical application of the optimization methods presented in this seminar.

Gear engineers, gear designers, application engineers, people who are responsible for interpreting gear designs, technicians and managers that want to better understand all aspects of gear design would benefit from this course.

The majority of the course material is presented through qualitative descriptions, practical examples, illustrations and demonstrations, which require basic mathematical and engineering skills. However, some familiarity with gear design and application will enhance overall understanding of the material.

After taking this course, attendees will be able to improve gear designs, better understand gear rating theory and analysis methods, investigate differences in stress states among various surface durability failure modes, discuss time dependent and time independent failure modes related to tooth design, use computer generated graphics to examine mesh action and tooth interaction, and gain new insight into the concepts presented through illustrations and demonstrations. Register here: *www.agma.org/education/online/video-training/detailed-gear-design-beyond-simple-service-factors/*

Rexnord Falk School

Rexnord Falk School is a three-day course designed to provide students with a basic understanding of the fundamentals of gear drive assembly and disassembly. It provides a unique, hands-on opportunity for maintenance professionals to learn from instructors with vast field experience. Using step by step instructions, Rexnord instructors make maintaining gearboxes simple, so participants leave with the confidence of knowing how to apply the material to increase reliability and avoid unscheduled outages. Training includes gear drive, bearing, and couplings maintenance procedures, assembly and disassembly of gear drives, how to adjust tapered roller bearings to obtain proper float or preload, how to install bevel gearing and adjust to optimize contact, how to enhance gearbox reliability through continuous monitoring, troubleshooting techniques, and basic failure analysis. The upcoming in-person class schedule in Milwaukee, Wisconsin includes September 15-17, October 6-8, and November 10-12. Classes follow strict social distancing protocols/mask mandates. Register at *www.rexnord.com/falkregistration.*

Masks off only for a photo-op at a recent training course at the Rexnord Falk School.

TPC Training — Mechanical Drive Maintenance

This online training course covers alignment, particularly coupling alignment. It includes installation and maintenance of mechanical drives, from chain drives to enclosed gear drives. Mechanical Drive Maintenance is available in two formats: online maintenance training and course manual. The online format provides a comprehensive library of online maintenance training with content-rich, interactive courses. The course manual format provides a fully customized courseware including safety training videos/DVDs, and instructor support materials. They also provide customized textbooks for technical schools. Register here: *www.tpctraining.com*

Investing in the Future

In addition to keeping in-house talent trained and educated, the push for bringing in young talent — college and high school students — continues to gain momentum in STEM fields.

NORD Drivesystems, for example, is investing heavily in training young talent and offers a wide range of entry opportunities into commercial, business, and technical fields. This includes actively participating in internships and college education programs, school factory tours and training fairs. Nord's flexible applications, diverse products, and its continuous technology push helps to engage interest from students seeking a potential manufacturing career path.

For Lenze, a total of 40 new trainees and students will start their professional careers throughout Europe in 2020. The company balances sound technical know-how and the correct handling of hardware and software just as much as team spirit and mutual respect. This year, 40 young people are eager to become part of the international Lenze team and thus set the course for their professional future. "Vocational training is an important investment in the future—for Lenze as well as for the new colleagues themselves," said Christian Wendler, CEO Lenze SE.

As an employer, Lenze focuses on innovative learning concepts, individual support, and traditional values such as trust, cooperation, and responsibility. Digitization and automation also play a prominent role at Lenze. Thus, central future topics such as predictive maintenance, digital twin or big data management are already being addressed today. This content is also reflected in the training content and ensures that the new trainees and students have a promising start to their careers.

In 2020, employees would also benefit from a better understanding of Industry 4.0, big data, the digital twin, etc. Preparing your workforce for these IIoT technologies is important today as shop floors transform into factories of the future. Why not take advantage of any downtime to get your workforce up to speed on the changing role of smart manufacturing in your plants?

A pre-pandemic photo of the Rexnord Falk School in Milwaukee, Wisconsin

The Training Continues

Schultz has spent many weeks on the Gear Talk blog (*www.geartechnology.com/blog/*) covering the importance of training and educating gear personnel.

"Once you really *know* your job you start to wonder about why things are being done in a certain way. Absent a good mentor, you need to do your own research on those topics using books, online resources, and, hopefully, high-quality continuing education. As your knowledge grows, you will start to think about that next step up the ladder," Schultz said. "No one gets promoted for just doing their job. You can pay for lots of online training for the money you otherwise spend on recruitment fees. Spend time getting to know your team. Identify the training they need. Sign them up for those classes and give them a chance to shine."

Employee skill development can't stop during a pandemic. Companies *must* come up with new and innovative ways to bring new talent through the front door and keep the talent they already have. If this means spending more time in a Zoom meeting or wearing a mask during a live gearbox demonstration—so be it. The work never stops, it simply evolves over time. **PTE**

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Comparing Data Sources for Condition Monitoring Suitability

M. Fromberger, S. Sendlbeck, M. Rothemund, J. Götz, M. Otto and K. Stahl

Introduction

In our industrialized world, power transmissions form an essential component of many machines that enable our way of living; machines are part of human agriculture, mobility, civil engineering, electricity generation or medicine, to name but a few.

Many of these power transmissions rely on gears as a main element. A big part of this huge amount of gears consists of cylindrical gears with involute tooth flank shapes.

The applications these gears are part of vary widely with regard to cost, transmitted power and consequences of failure. These aspects — among others — also influence the maintenance strategy that is applied to a given gear set.

Figure 1 shows the service life of a machine part and shows when three different maintenance concepts become active during the part's life.

Different strategies of maintenance exist (Refs. 7, 10):

Preventive maintenance covers concepts in which parts are replaced or repaired according to a schedule; generally, without the machine or the part being critically damaged. This approach is often used when failure has severe consequences and monitoring the actual condition of the machine is chosen not to be done.

Corrective maintenance covers approaches that react on failures. A part or machine is repaired or replaced when the end of life of a machine or part is reached. This often is used for applications where stand-still has no severe consequences or where failure of single parts is non-critical due to redundancy.

Condition-based maintenance on the other hand tries to identify the current state and/or the remaining service life of a machine or part as accurate as possible, thus allowing for an optimized usage of the available service life. Opposed to the other two concepts, condition-based maintenance requires detailed state knowledge, often acquired by means of sensors.

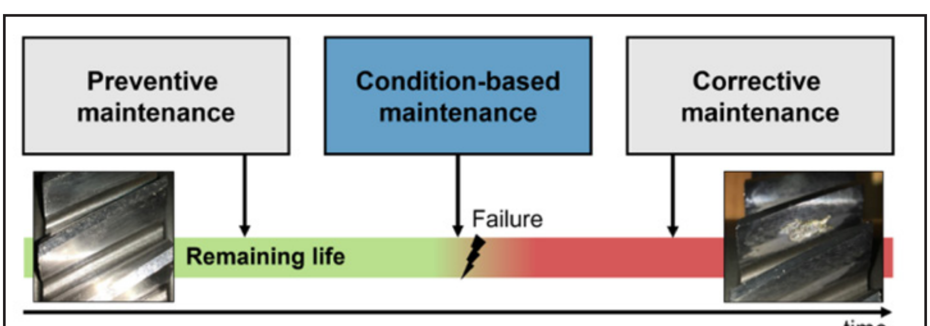

Figure 1 Different maintenance approaches.

Gear Condition Monitoring and Gear Damage Detection

This section illustrates the boundary conditions and relevant mechanisms that come into play if condition-based maintenance is to be applied to cylindrical involute gears, and how signals can be processed for condition monitoring.

Basics of involute gears and their vibration excitation behavior. As mentioned, the dominant flank shape of gears is the involute. The kinematics of an involute-shaped gear pair allows for a uniform transmission of the rotational movement (i.e. — zero transmission error) of the driving gear to the driven gear — given that deflection and deviations are disregarded.

Generally, real involute gear pairs excite vibrations when operating under load. Mounting and manufacturing deviations influence this behavior, but even perfectly involute-shaped gear pairs excite vibrations due to time-varying gear mesh stiffness and the corresponding elastic deflection. This mesh stiffness is well-described and understood (Ref. 9), and depends on various influence parameters, such as number of teeth pairs in contact, bending lever, radii of curvature at current mesh position, gear macro geometry (face width, tooth height, tooth thickness, etc.) and flank micro geometry (flank shape deviations and also intentional modifications (Ref. 13).

This time-varying gear mesh stiffness results in a time-varying loaded transmission error (LTE), which more or less corresponds to the vibration excitation of a gear mesh, depending on the dynamic operating point of the system.

Figure 2 shows a transverse section of a spur gear mesh for two meshing positions. The upper-left mesh is in a position where just one pair of teeth is in contact. The upper-right image shows the same mesh in a different position where two tooth pairs are in contact.

The diagram below those two meshing images shows the course of mesh stiffness and LTE, with the two shown discrete meshing positions marked as vertical lines.

This paper was first presented at the International VDI Conference on Gears 2019, 3rd International Conference on High Performance Plastic Gears 2019, 3rd International Conference on Gear Production 2019, Garching/Munich (VDI-Berichte 2355, 2019, VDI Verlag GmbH, Page 257–268)"

The vibration measured at the gearbox case can be composed by many different vibration sources, e.g. — more than one gear stage (Ref. 14).

Not only manufacturing deviations of the gear flank shape, along with intentional deviations from the ideal involute to positively influence excitation behavior (Ref. 6), but also flank shape changes that occur during operation (e.g. — due to running-in and especially due to damages) have impact on the vibration excitation behavior of a gear mesh. Consequently, vibration excitation of gears can be relevant for noise (and thus can be a design criterion for applications relevant to human audibility, e.g. — automotive gearboxes (Ref. 2)) as well as for condition monitoring. Using gear-excited vibration to monitor gear condition has been under research for decades, with researchers often specializing on specific damage mechanisms, e.g. — wear or scuffing (Refs. 1, 4).

Figure 3 shows a selection of gear damage mechanisms relevant in practice with example photographs and some of their properties. Detailed descriptions of many relevant gear damage types are found in ISO 10825 (Ref. 5).

This and the generally simple application of picking up acceleration signals are two reasons why many gear condition monitoring approaches in research, as well as in industrial practice, rely on vibration/acceleration data as main measurement value.

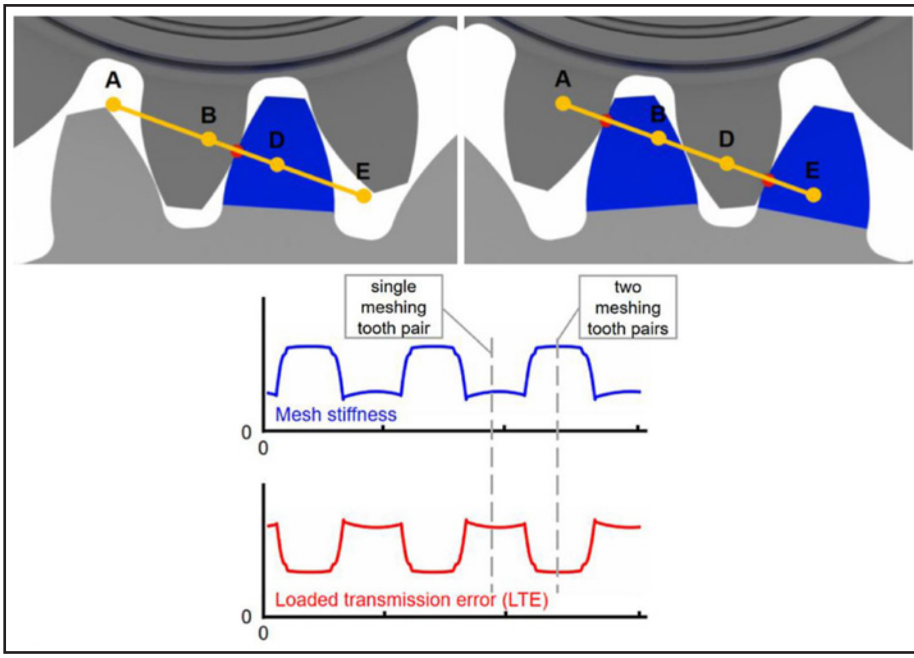

Figure 2 Meshing positions and corresponding mesh stiffness and LTE.

Damage mech.	Example	Typical location (at tooth)	Typical location (at gear)	Mechanism / progress
Pitting		below pitch circle	specific teeth	contact fatigue
Micropitting		below pitch circle	specific, soon all teeth	contact fatigue
Scuffing		towards tip	specific teeth	non-fatigue
Tooth root fracture		30° root tangent pt.	specific teeth	bending fatigue
Flank fracture		below flank surf.	specific teeth	inclusion origin
Adhesive wear		sliding regions	all teeth	mixed EHL regime

Figure 3 Summary of typical gear damage mechanisms and some of their properties.

Data acquisition and signal processing. Acceleration signals are in practice often accompanied by various kinds of angular data, ranging from simple shaft speeds (i.e. — tacho signals) to full-fledged high-resolution and high-frequency absolute angular position signals of the shafts of a to-be-monitored gear stage.

Having additional angular data enables various processing techniques for the acceleration data. One example is applying order tracking to eliminate cyclic irregularity by transforming acceleration time-series into angle-series. This is the standard approach of order tracking, although tacho-less order tracking techniques do exist (Refs. 8, 12).

Another example is tooth-specific condition monitoring. Using sufficiently precise angular data, acceleration signals can be split into per-tooth signals. These sub signals can then be compared with regard to e.g., their signal power (Ref. 3). This allows for detection of damage that occurs on single teeth (e.g., pitting) and not nearly uniformly over all teeth (e.g., wear). This technique has the benefit of not needing external references (such as "passed" EOL test measurements), as the reference for each tooth can be e.g., the mean per-tooth signal power of the gear itself.

Choosing the right sensor equipment is not trivial. Available acceleration sensors vary in many properties. Some of these properties are suitability for intended condition monitoring application (frequency response, frequency range, sample rate), requirement for supply current; shock, temperature and chemical resistance, and cost.

When deciding about angular information sources, similar considerations are required; if cyclic irregularity is small, simple tacho signals may suffice. If the machine in question is operating highly dynamic, more samples-per-rotation than just one or few (as often with tacho signals) may be required, directing the choice towards high-end angle encoders.

When considering angle encoders, the choice absolute vs. incremental must be made; incremental encoders can be very accurate, but limited with regard to rotational speed (Ref. 11).

Absolute encoders allow for tracking absolute angle position over long times without having to reference to additional zero-pass signals or having to reliably add up increment counts.

Comparison of a Low-End and a High-End Sensor Setup

Figures 4 and 5 illustrate the DAQ systems used for the tests.

The higher-end DAQ system was chosen to provide maximized accuracies and sample rates, using angle sensor used in e.g., tool machines, and accelerations sensors at the upper end of the market spectrum. The sensors are coupled with low-noise acquisition hardware capable of matching the sensor specs. The acceleration sensor has been screw-mounted directly into the bearing cover of the gearbox to provide best coupling stiffness and a short transfer path towards the point of excitation (i.e. — the gear mesh).

The lower-end DAQ system was chosen to meet low-cost requirements and was assembled picking consumer-grade or lower-end industry-grade hardware. The acceleration sensor was glued onto the bearing cover using epoxy.

For comparison purposes, tooth root breakage test vibration data was evaluated at tests where the gear's load carrying capacity was researched. The testing machine was an FZG standard back-to-back test rig with a center distance of 91.5 mm.

In this publication, both sensor setups were not used simultaneously due to hardware availability issues at testing site. Thus, different tests are shown which are named experiment A and B; but test gear geometry and testing conditions are equal. Both tests failed rather quickly after the initial crack by tooth root breakage of one single tooth, after a (shorter, A, or longer, B) rather uneventful phase of testing.

Raw data. Using both setups, acceleration (and rpm/angular) signals were acquired.

Figure 6 shows extracts of lower-end (upper-half of figure) and higher-end (lower half) acceleration sensor data, acquired using the setups described before; they both show a duration of 0.05s. Amplitudes are normalized. The much lower sample rate of the lower-end setup is obvious: higher-frequency signal components are only resolved using the higher-end setups.

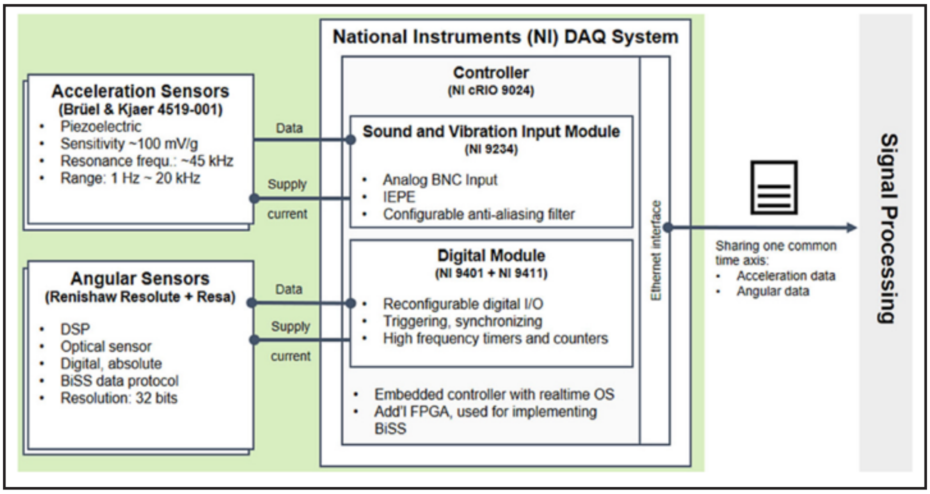

Figure 4 Higher-end DAQ systems used for tests.

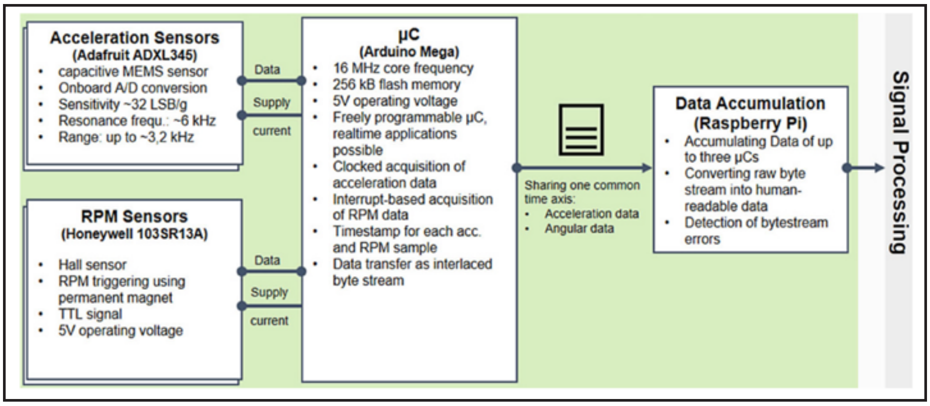

Figure 5 Lower-end DAQ systems used for tests.

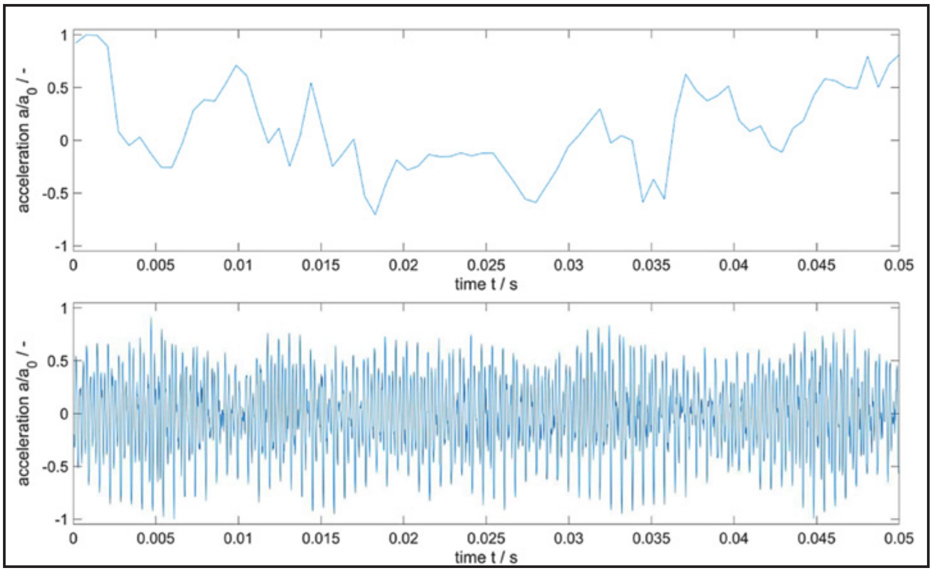

Figure 6 Extract of raw acceleration data.

Experiment Evaluation

For evaluation, the acceleration time series has been split into tooth-specific sectional sub signals without overlap. The angular segments corresponding to each tooth section have been chosen iteratively in a way to reach maximum signal power for one single sub-signal in combination with a preferably high distance to the second highest section for the last measurement before total gear failure. This could also be done on the fly for each measurement. When using high-accuracy absolute angle encoders, a direct correlation of meshing position and shaft angle is also possible.

Figure 7 shows normalized acceleration signal power data (tooth-specific) of the rather short-running tooth root strength experiment A. A short-running test was selected on purpose. This requires facing the challenge of separating settling processes from damage processes. The normalized time axis accounts for the period from start of experiment to end of experiment by failure. This test was so short-running that running-in and settling processes (high and decreasing signal power in the corner areas of the diagram) partially collide in time with the subsequent damage event (increasing signal power around tooth 10).

To be able to separate settling effects (= decreasing per-tooth signal power over time) from damage events (= increasing signal power), the per-tooth signal power time series were sorted according to increase and decrease rates respectively across all measurements.

Figure 8 shows the result of such a pre-processing: The normalized per-tooth signal power series of the five most increasing time series across all measurements (on an also normalized time base).

Figure 9 shows another experiment B. For that the higher-end measurement setup was used.

This test was longer running until failure by tooth root breakage. There were no noticeable signal power increases for a longer operating time. Within the last approx. Four percent of the operating time before failure a significant increase of one section's signal power can be observed.

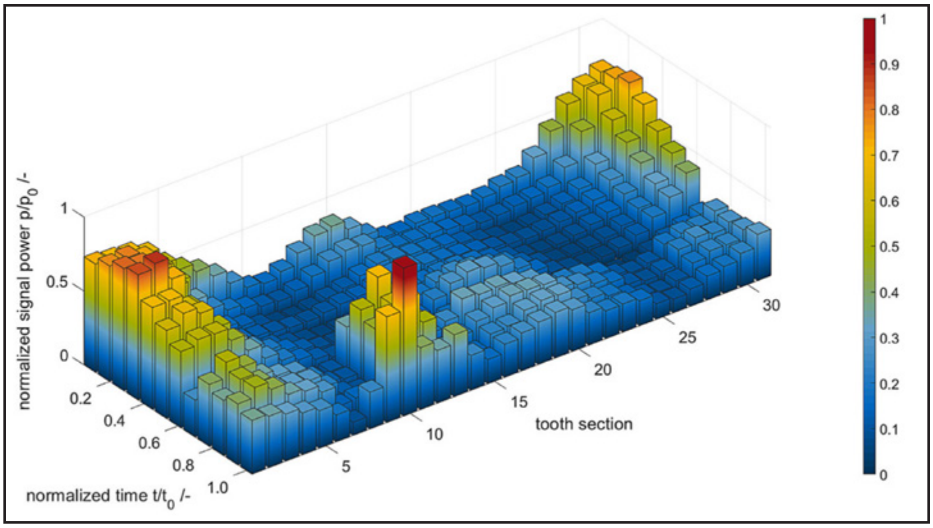

Figure 7 Lower-end data, experiment A.

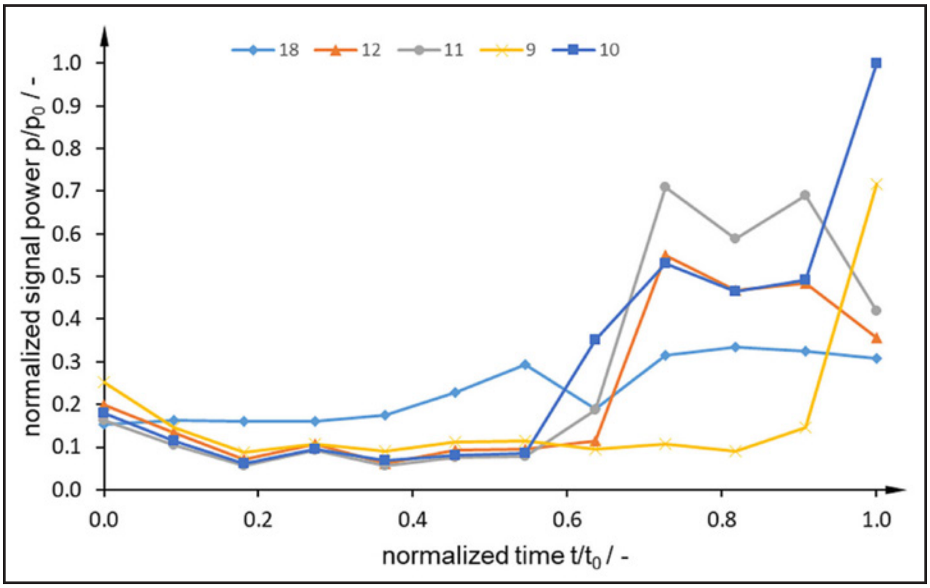

Figure 8 Per-tooth signal power (5 most increasing) of experiment A.

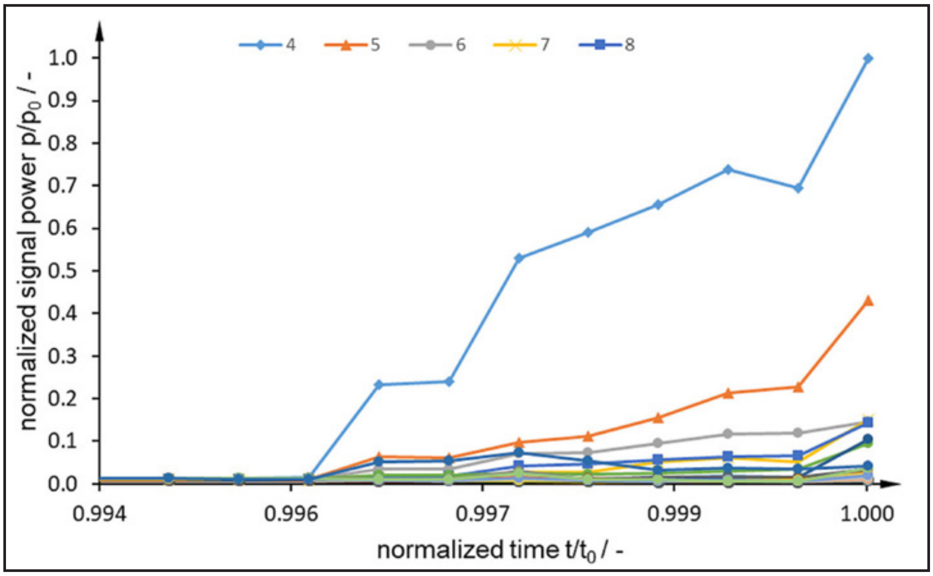

Figure 9 Per-tooth signal power (5 most increasing) of experiment B.

Conclusion

Several conclusions can be drawn by looking at these two tests' results:

- Significant changes of relative per-tooth signal power observable in both setups
- Signal-to-noise ratio is significantly better when using the higher-end setup (see stable signal power phase at left of Fig. 9)
- Isolation of angular position contributing most power more precisely with higher-end setup
- Pre-selecting tooth signals by sorting the sub-signals (most increasing power first) allows isolating settling effects from damage, as long as one of the following is true:
  - » damage signal power contribution is significantly larger then signal power contribution of pre-settling state
  - » locations of damages are separable from the location of pre-settling signal power contributing locations

We plan to assemble and evaluate a larger database of both kinds of data. Additionally, evaluating data of the exact same tests using both measurement setups simultaneously is planned.

For more information.

Questions or comments regarding this paper? Contact M. Fromberger at *fromberger@fzg.mw.tum.de*

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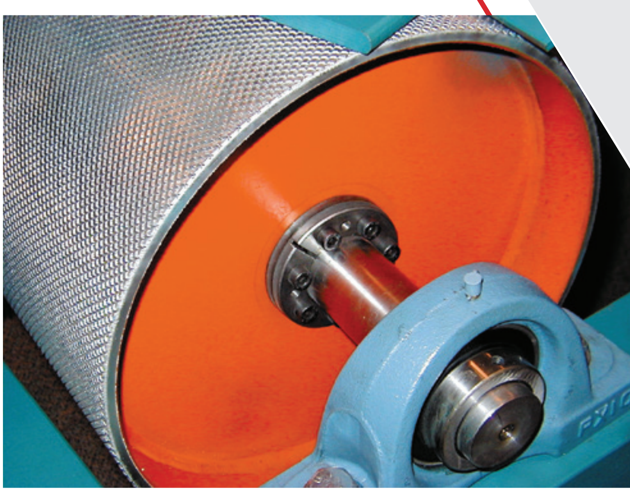

Various Coil Configurations Used in Coreless Motors

Clyde Hancock

Introduction

There exists a type of DC motor known as a coreless or slotless motor. The main feature of this type of motor is the fact that there is no iron (core) associated with the coil. This means that there are no iron losses; no cogging torque; the inductance is lower than that of typical iron cored motors (less sparking of the commutator); the rotor mass is lower so they have very high acceleration rates; and they are excellent for low-voltage operation when using precious metal brushes. These motors are typically around 1 mm to 70 mm in diameter. These motors are found in pagers, medical devices (i.e. — insulin pumps), pick-and-place robotics and more. There are many different coreless coils available today for both mechanical and electrically commutated DC motors. A few are pictured in the appendix at the end of this paper. This paper will investigate several coreless coils. This investigation is limited to radial gap devices. Three-dimensional finite element analysis (FEA) simulation as well as research from published information is used to compare the features of the various coil configurations.

I have been involved with the design and application of motors and generators for the past thirty nine years. Throughout this period, I have been asked about the advantage of one style of coreless coil as compared to another. Which one is the best? On the surface, this seems to be a question with a rather simple answer. Coil A is better than coil B, C, or D, etc. However, this is not the case; the criteria used to judge the merit of one coil versus another is instrumental in making a valid decision. A list of items to consider for the comparison includes, but is not limited to, the magnetic circuit, copper density, end turn losses, and ease of manufacturing. All of these items contribute to the overall quality of the design, and each style may have advantages based solely on an individual attribute.

In the next section (II), a variety of coils are described and a computer model of each is developed for analysis. In Section III, an approach for comparison of coils based on catalog information is presented. Section IV consists of the results from FEA and catalog comparisons. Section V summarizes what has been done in this analysis and conclusions presented based on the results, as well as suggestions for future research.

Coil Decriptions and FEA Models

This investigation compares six coil styles (Fig. 1); Faulhaber, hexagon, rhombic, parallel, multiple Saddle, and Saddle. The first four are constructed using the "combined turn coil" method provided by the FEA software (Figs. 2-5). This feature allows the user to describe the coil by individual arcs, segments, and dimensions. The last two use built-in coil geometries available in the FEA software (Figs. 6-7). The geometric shape is fixed, while the dimensions are defined by geometric parameters. Inside and outside diameter of the coils are the same. The lengths of the coils constructed via the "combined turn coil" method are the same and represent the axial length of the magnet. The saddle style coils provided by the FEA software have end turn length extending past the axial length of the magnet. First the coils are modeled without permanent magnets or steel. The coils are energized with DC current that is arranged as a three-phase delta connection. Post-processing cylinders are constructed for the inside, center, and outside diameters of the coils; this allows the viewing of the fields generated by the coils themselves. Next, a diametrically magnetized two-pole permanent magnet is added to the inside diameter of the coil with a steel ring added to the outside diameter of the coil (Fig. 8). The coil has a radial air gap on each side. A torque profile is constructed by rotating the permanent magnet with respect to the energized coil for 360º in 10º increments and solving for the torque developed at each position.

The Faulhaber coil is unique in that it is a complete freestanding coil after the winding process is complete. The first half-turn of the Faulhaber coil traverses the full length of the winding in an oblique direction through 180° of rotation. The second half returns the length of the winding through another 180° of rotation (Figs. 1A and 2A). The remaining turns are indexed and wound to form a complete coil (Fig. 2B). Loops (not shown) are pulled at the end of the coil during the winding process in intervals that correspond to the separate segments or phases.

The remaining coils in this comparison require additional steps to achieve the final cylindrical shape. The hexagon, rhombic and parallel coils (Figs. 1B, 1C, 1D, 3A, 4A and 5A) are wound on a mandrel that establishes the shape of the coil, i.e. — hexagon, lozenge or diamond, and rectangle, respectfully. After the winding is completed, the coil is removed from the mandrel, flattened, and rolled into a coil (Figs. 3B-5B). Loops (not shown) are pulled for segments or phases, as in the Faulhaber coil.

The saddle and multi-saddle coils are wound as individual coil sections (Figs. 1E, 1F, 6A, and 7A). After winding, the coil sections are formed and placed in position for the final coil assembly (Figs. 6B-7B). Each coil has a start and finish that must be interconnected with the appropriate coils to establish the segments or phases.

In all cases, the coil inside diameter, outside diameter, number of turns, and applied current are the same.

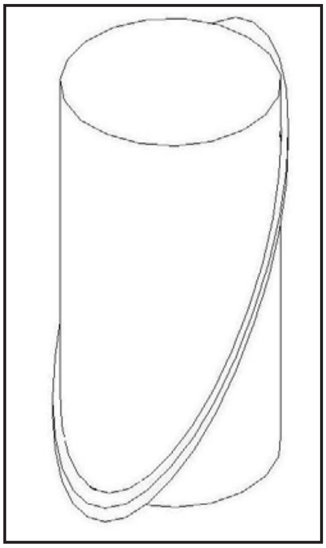

Figure 1A Faulhaber Coil.

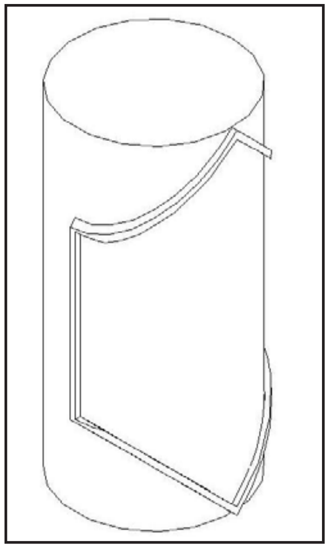

Figure 1B Hexagon Coil.

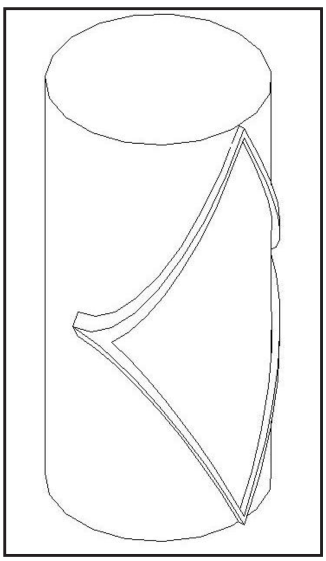

Figure 1C Rhombic Coil.

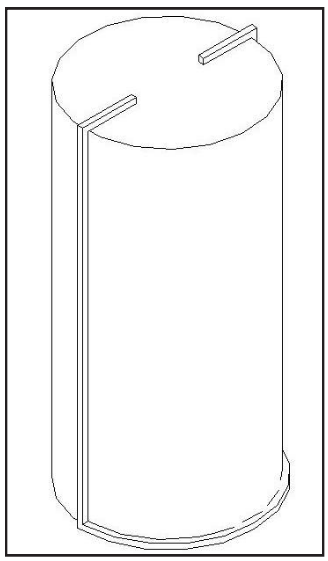

Figure 1D Parallel Coil.

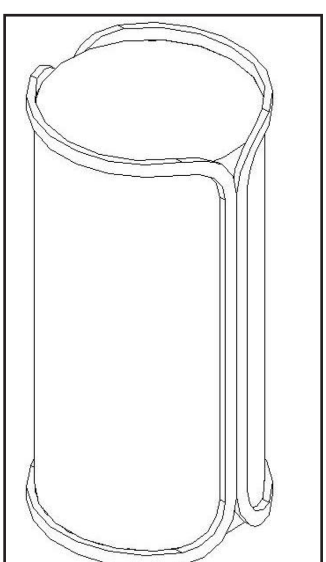

Figure 1E Multiple Saddle Coil.

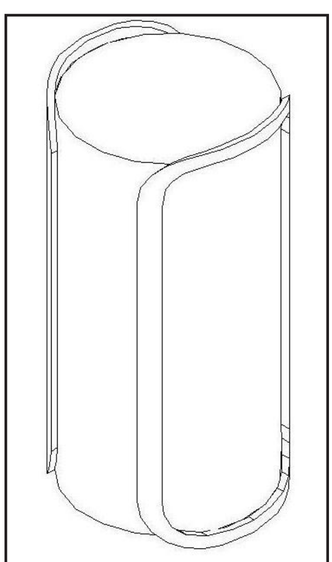

Figure 1F Saddle Coil.

Figure 1 Various Coil Shapes.

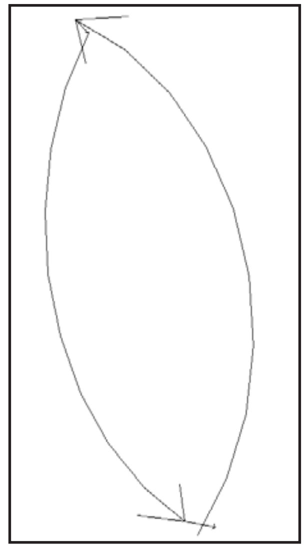

Figure 2A Single Turn of Faulhaber Coil.

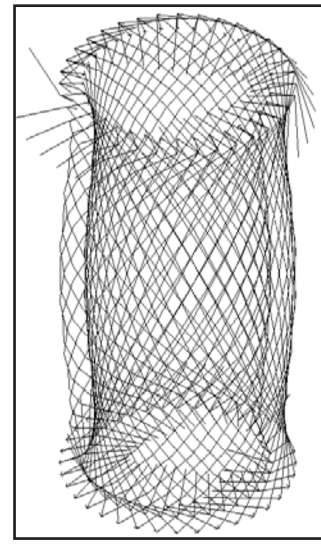

Figure 2B Complete Faulhaber Coil.

Figure 2 FEA Model of Faulhaber Coil.

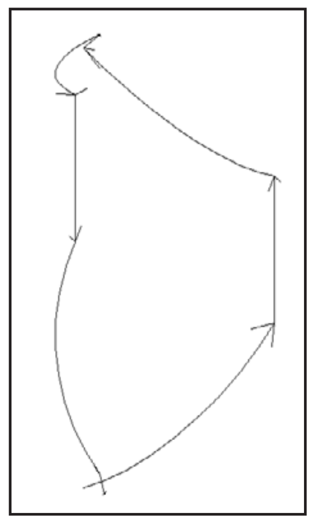

Figure 3A Single Turn of Hexagon Coil.

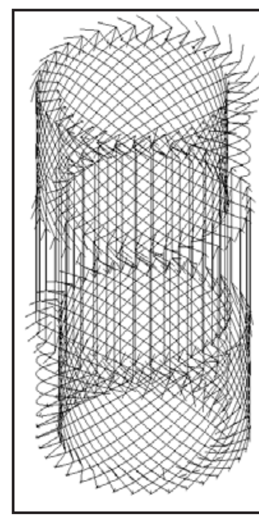

Figure 3B Complete Hexagon Coil.

Figure 3 FEA Model of Hexagon Coi

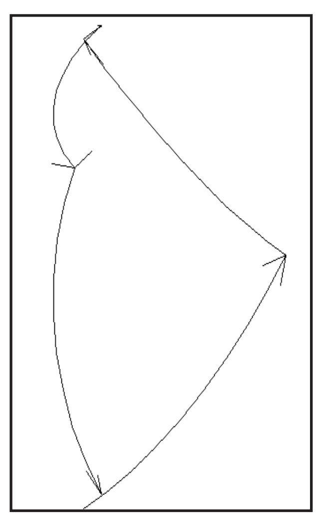

Figure 4A Single Turn of Rhombic Coil.

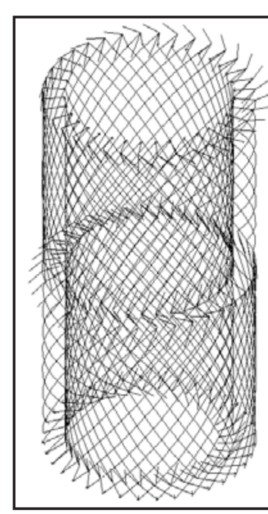

Figure 4B Complete Rhombic Coil.

Figure 4 FEA Model of Rhombic Coil.

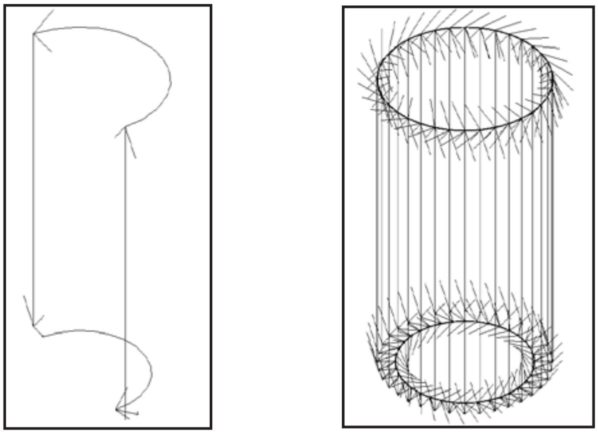

Figure 5A Single Turn of Parallel Coil.

Figure 5B Complete Parallel Coil.

Figure 5 FEA Model of Parallel Coil

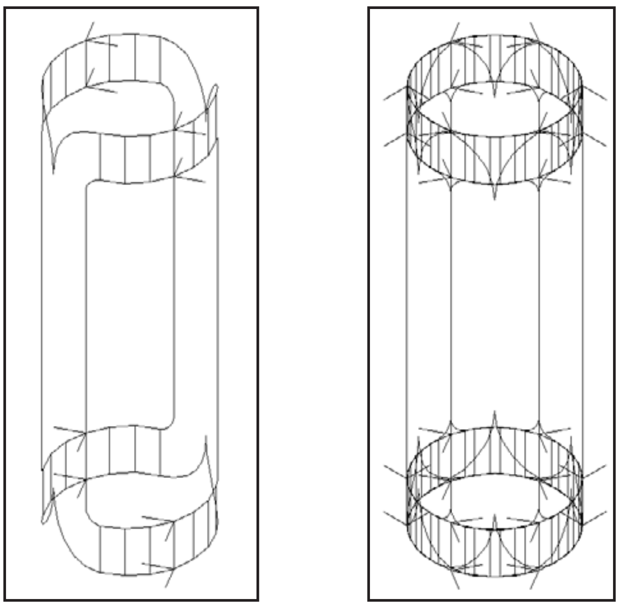

Figure 6A Single Phase of Multiple Saddle Coil.

Figure 6B Complete Multiple Saddle Coil.

Figure 6 FEA Model of Multiple Saddle Coil.

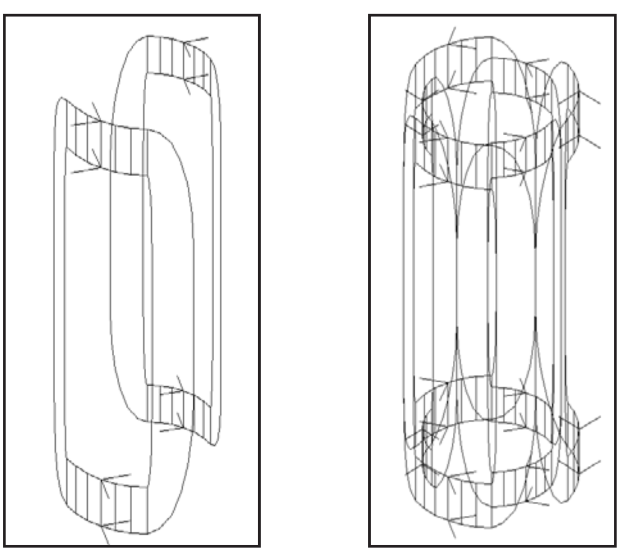

Figure 7A Single Phase of Saddle Coil.

Figure 7B Complete Saddle Coil.

Figure 7 FEA Model of Saddle Coil.

Catalog Data Comparison

A comparison of catalog data is interesting — though not conclusive. The data published in the catalog does not detail the inner workings of the motors. The number of turns, the dimensions, and the diameter of the wire used in making the coil are not published. In addition, the material, size, and grade of the magnet are unknown. Two coil styles are readily compared, i.e. — the Faulhaber and the rhombic. Some manufacturers do not publish the type of coil that they employ in their product. Moreover, the size and power of motors manufactured using the various coils are not always comparable. The Faulhaber coil was patented and is used by several manufacturers with published data. The method of producing the hexagon coil was patented by Eastman Kodak and the rhombic coil is used by at least one manufacturer with published data.

A motor size is chosen to establish a common ground for comparison. The length and diameter as published in the catalog should match as closely as possible. Next, the winding constant is considered and matched accordingly. This establishes motors from different manufacturers with equivalent torque-per-amp-per-volume. The parameters for comparison include resistance, inductance, maximum power, and thermal resistance.

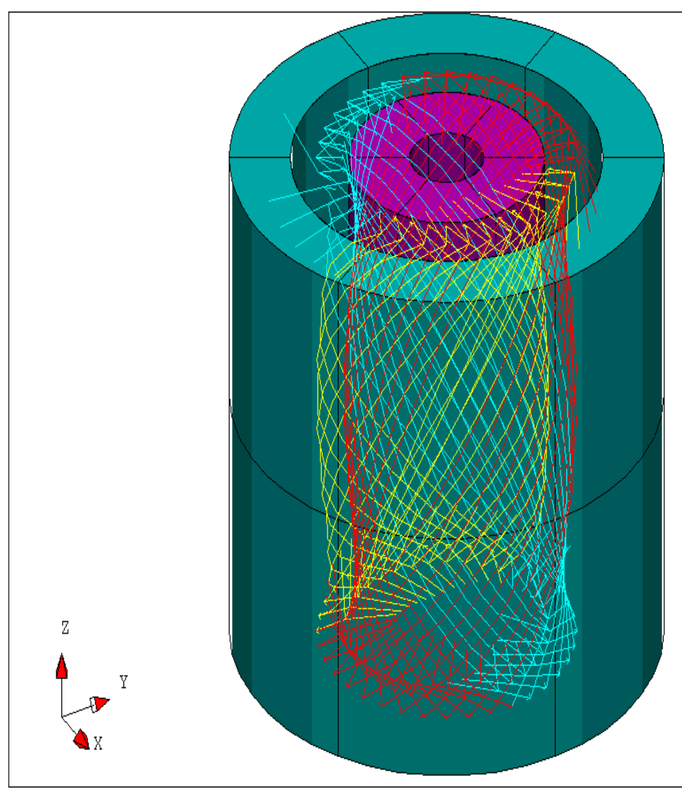

Figure 8 Example of Complete Model for the Faulhaber Coil
- Magnet Inside Diameter: 4.87 Mm
- Magnet Outside Diameter: 12.87 Mm
- Coil Inside Diameter: 13.55 Mm
- Coil Outside Diameter: 17.15 Mm
- Steel Return Inside Diameter: 20.58 Mm
- Steel Return Outside Diameter: 28.58mm
- Axial Length: 27mm

Results of FEA and Catalog Comparison

Results generated by the FEA comparison for the coils alone are viewed in the post processor. A relief map of the inner and outer diameter depicts the intensity and shape of the magnetic flux density in the theta direction using the cylindrical coordinate system *R*, θ, and *Z* (Figs. 9-14). The magnetic flux density in Tesla is represented by color on the scale to the right. The relief map shows the per-unit axial length of the post-processing cylinders on the *y* axis, and the per-unit circumference on the *x* axis. Interpretation of the relief maps is somewhat subjective. The relief maps afford the ability to see the relative shapes and intensity of magnetic flux density for the various coil geometries.

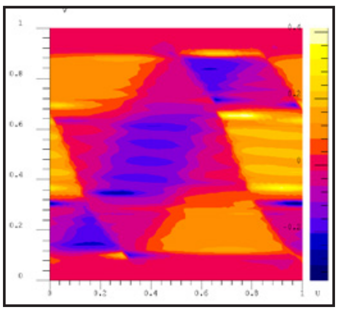

Figure 9A Faulhaber Coil ID Magnetic Flux Density.

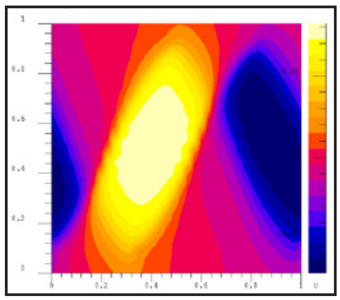

Figure 9B Faulhaber Coil OD Magnetic Flux Density.

Figure 9 Magnetic Flux Density in θ Direction for the Faulhaber Coil.

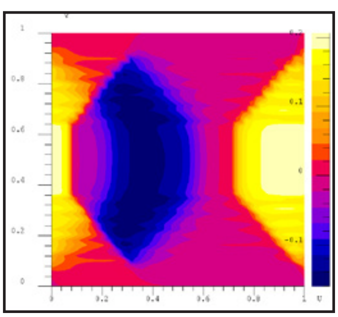

Figure 10A Hexagon ID Magnetic Flux Density.

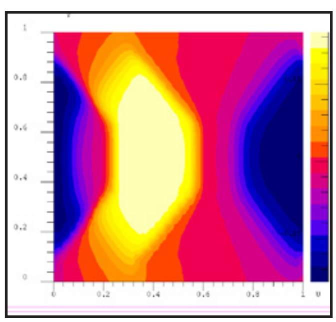

Figure 10B Hexagon OD Magnetic Flux Density.

Figure 10 Magnetic Flux Density in θ Direction for the Hexagon Coil.

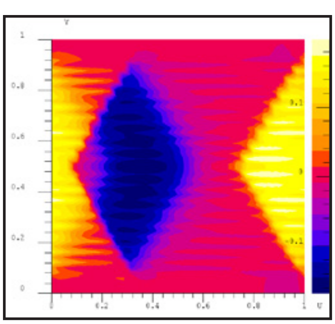

Figure 11A Rhombic ID Magnetic Flux Density.

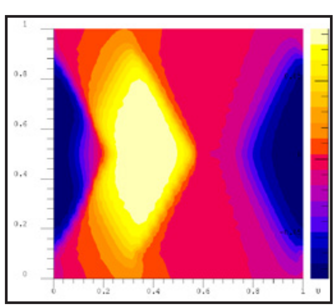

Figure 11B Rhombic OD Magnetic Flux Density.

Figure 11 Magnetic Flux Density in θ Direction for the Rhombic Coil.

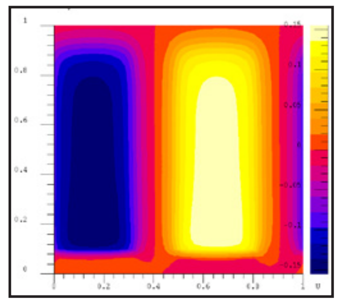

Figure 12A Parallel ID Magnetic Flux Density.

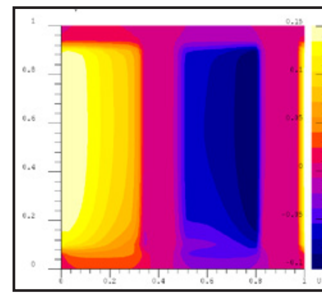

Figure 12B Parallel OD Magnetic Flux Density.

Figure 12 Magnetic Flux Density in θ Direction for the Parallel Coil.

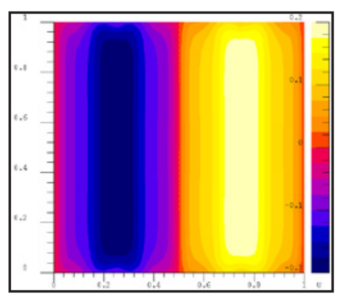

Figure 13A Multiple Saddle ID Magnetic Flux Density.

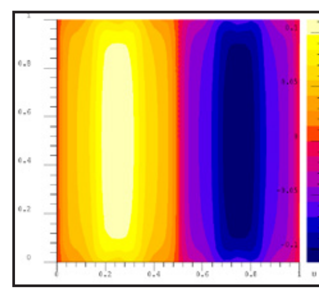

Figure 13B Multiple Saddle OD Magnetic Flux Density.

Figure 13 Magnetic Flux Density in θ Direction for the Multiple Saddle Coil.

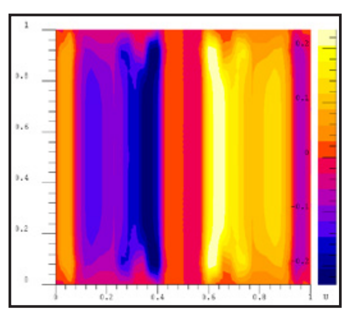

Figure 14A Saddle ID Magnetic Flux Density.

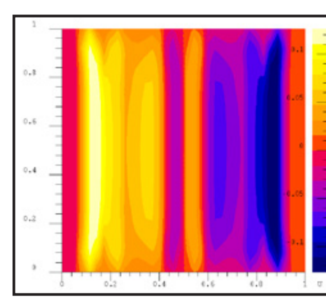

Figure 14B Saddle OD Magnetic Flux Density.

Figure 14 Magnetic Flux Density in θ Direction for the Saddle Coil.

The results of the torque profiles generated by the FEA models are represented (Fig. 15). The graph depicts the torque for each of the coil styles studied. The values on the graph's *y* axis represent the measured torque between the stationary portions (coil and steel return) and the rotated portion (magnet) in 10° increments for one full revolution; the current and number of turns are the same for each coil.

Table 1 shows comparisons for manufacturers "A" vs. "B" and "A" vs. "C". Manufacturers "A" and "C" are Faulhaber coils; manufacturer "B" is a rhombic coil. In all cases, the motors being compared have the same outside diameter. The lengths were selected to be as close as possible; however they vary in some cases. In the column labeled K_T, the shaded area colors match for the motor being evaluated. The column labeled $P_{2\,max.}$ is calculated with the recommended nominal voltage, resistance, and no-load current.

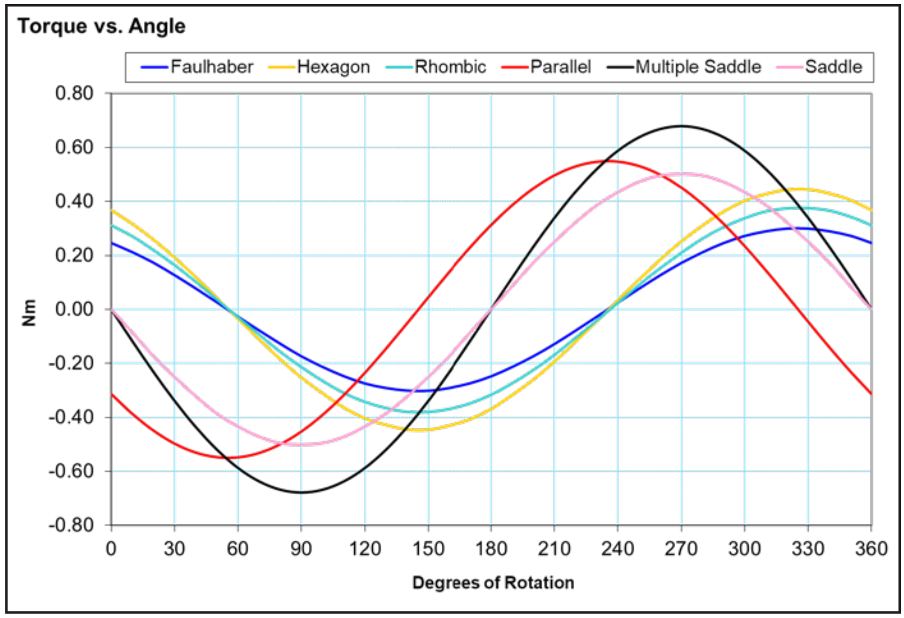

Figure 15 Torque vs rotor position.

Table 1 Comparison of Published Catalog Data for Manufacturers A, B, & C

Manufacturer	Diameter mm	Length mm	Nominal Voltage	Speed NL RPM	KT Nmm/A	R W	L mH	Rth 1 °C/W	Rth 2 °C/W	KM Nmm/√Watts	INL A	P2 max. Watts
A	15	23.8	6	9700	5.8	5.1	0.070	4.5	31	2.568	0.021	1.702
			9	10100	8.37	10.4	0.150			2.595	0.014	1.885
			12	9900	11.4	19.8	0.250			2.56	0.011	1.753
			18	9900	17.1	44	0.560			2.58	0.007	1.778
			24	9900	22.8	79.6	1.000			2.56	0.005	1.750
B	15	22.3	4.5	7450	5.62	6.46	0.120	8.2	35	2.21	0.017	0.746
			7.2	7740	8.67	15.3	0.290			2.22	0.011	0.808
			9	7710	10.9	24.4	0.460			2.21	0.009	0.790
			15	8110	17.2	62.2	1.150			2.18	0.006	0.860
			24	9890	22.7	109	1.990			2.17	0.005	1.262
A	26	57	12	6300	17.3	0.79	0.095	1.9	9	19.46	0.116	44.876
			24	6400	34.8	3.2	0.380			19.45	0.058	44.307
B	26	58.8	18	9910	17.1	1.52	0.100	4.2	9.7	13.87	0.061	52.742
			36	10300	33.1	4.72	0.360			15.24	0.032	68.069
			36	9400	36.3	5.68	0.430			15.23	0.028	56.539
A	17	24	6	8600	6.61	3.41	0.075	4	24.5	3.58	0.023	2.571
C	17	25.9	6	8500	6.7	3.2	0.110	10	30	3.75	0.011	2.781
A	22	32.6	18	8700	19.6	25	0.600	4	27	3.92	0.007	3.177
C	22	32	12	5900	19.3	27	1.200	6	22	3.71	0.004	1.312
A	26	42	24	6400	34.6	5.78	0.550	2.1	11	14.39	0.058	24.222
C	26	42	24	6700	33.5	32	1.700	5	12	5.92	0.012	4.357
A	28	42	12	5100	22	5.3	0.580	2	16	9.56	0.050	6.496
			24	5000	44.8	21	2.500			9.78	0.025	6.560
C	28	42	12	5300	21.4	5.95	0.500	5	12	8.77	0.022	5.919
			24	5600	40.7	19.5	2.400			9.22	0.011	7.253

Conclusions

Based strictly on the FEA analysis, it is clear that there is an electromagnetic advantage to winding coils with certain geometric features. What is not readily apparent from the evaluation of a single conductor in a magnetic field is the overall effect of the geometry for a complete coil. The interaction of the conductors assembled as a coil would indeed be difficult to imagine without the use of tools that simulate the device in three dimensions. I believe that, although subjective due to scaling, the relief maps indicate preferred geometries for optimizing coils. The torque observed for the various coils also demonstrate that there are preferred geometries.

The comparisons of catalog data are minimal; they indicate that there is more than just a difference in the coil shape. Alternative methods of fabricating the coil are a factor. As seen in Table 1, Manufacturer "A" motors are consistently lower in the reported coil thermal resistance ($R_{th\,1}$) than either "B" or "C" motors. After disassembling samples of the motors, it was noted that both "B" and "C" motors use some sort of wrapping on the outside diameter of the coils. This of course acts as insulation. This would leave less room for copper (smaller-diameter wire) or require larger air gaps. This may account for the higher resistance seen in the table.

This study, although interesting, is not conclusive. Much more work could be done in areas such as length-to- diameter ratio effects, state of the art winding techniques, and the number of permanent magnet poles with respect to the number of coil segments or phases.

If your application requires high acceleration, low sparking, zero cogging, and no eddy current loss, then you should consider the coreless DC motor. Some of the manufacturers that offer this type of motor are (in alphabetical order) Baumüller, Canon, Citizen Micro, Dunkermotoren GmbH, Faulhaber GmbH, Namiki Precision Jewel, Portescap S.A. and more. Automated (or semi-automated) winding equipment is available for all of the coil configurations mentioned. **PTE**

Appendix

Index Terms: Coreless, ironless, voice coil, moving coil, basket-wound, slotless, rhombic, bell winding, and multi-saddle.

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Motor Consultants, LLC
August 3, 2020

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Hybrid Transverse Flux Magnetic Motors — How to Measure Parameters

Donald Labriola, P.E

These versatile, low-cost and high-torque motors may be used open loop or as full servos — and several levels in between. The motor stator laminate designs divide these motors into those optimized for full stepping, and those optimized for micro stepping and servo operation. These differences can be easily measured with basic meters and oscilloscopes. Motor to motor variations can also be easily measured, and motor inductance at nominal speed and current can also be determined.

There are two distinct designs of the stator for common two- phase 1.8 degree per step motors, each with its own advantages and disadvantages. Full stepping laminates and micro-stepping laminates (of which there are many variants). The full stepping laminates have the rotor and stator teeth on the same pitch. For a 1.8 degree motor, another name is 50:50 laminate: 50 teeth on each pole cap, and stator teeth on the same 50 tooth spacing (Fig. 1). Full stepping motors typically have a higher holding torque and a higher unpowered detent torque. The increased holding torque (for full step positions) is due to the detent torque aiding the torque at the full step positions. The detent torque is generated by having many of the rotor and stator teeth all align simultaneously, producing significantly lower reluctance path for the magnet in these motors when at the full step positions. The figure is from US5309051. This detent torque, is present even when power is removed from the windings, and may be used advantageously in applications such as continuous paper printers in that the platen has holding torque to resist motion even when powered down. This keeps the paper from unwinding on the floor when power goes out, without the need for mechanical brakes.

When the rotor of a permanent magnet motor is spun, the windings on the stator produce voltages due to the magnetic fields from the permanent magnet in the rotor being gated through the teeth of the rotor and stator, and producing time varying flux through the coils present in the stator. The voltages from the two windings can be viewed both versus time, and also as one winding versus the other, preferably while keeping a constant rotation speed. This is easily accomplished by spinning the shaft with a small electric drill motor. A large flywheel can also be attached to the shaft and hand spun with the output from one of the windings recorded over a several second time interval using a digital storage scope. (A USB scope which uses the memory of the PC gives good sampling rates over the long intervals). We will cover each of these techniques.

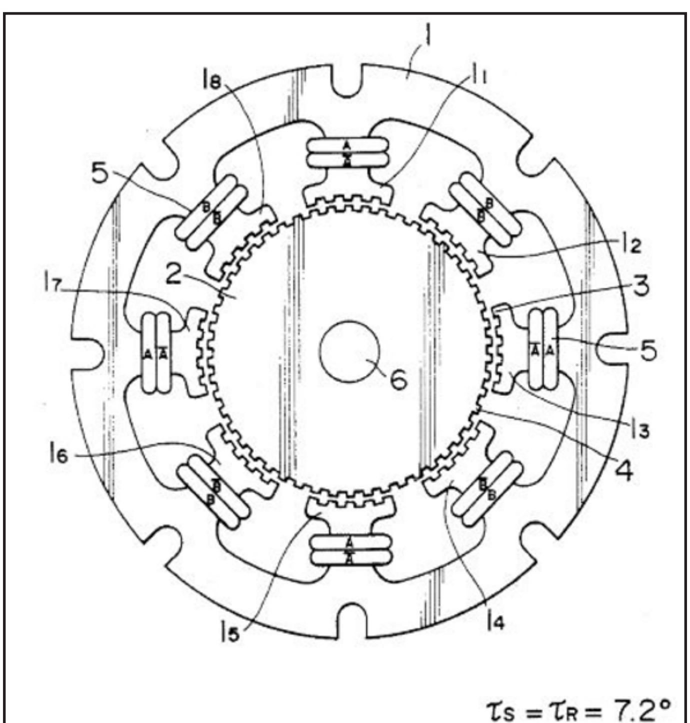


Figure 1 50:50 full step laminate.

Full-Step versus Micro-Step Optimized Motors

The oscilloscope channels of a 2-channel digital scope are connected to the motor and the motor is spun with a small power drill. The full step stepping motor produces a trapezoidal back-EMF when spun (Fig. 2). The phase lane chart is almost square with rounded corners (Fig. 3). The radius of the back-EMF pattern at a given angle represents the torque constant for that motor at that angle. The fact that the radius varies significantly with angle indicates significant variations

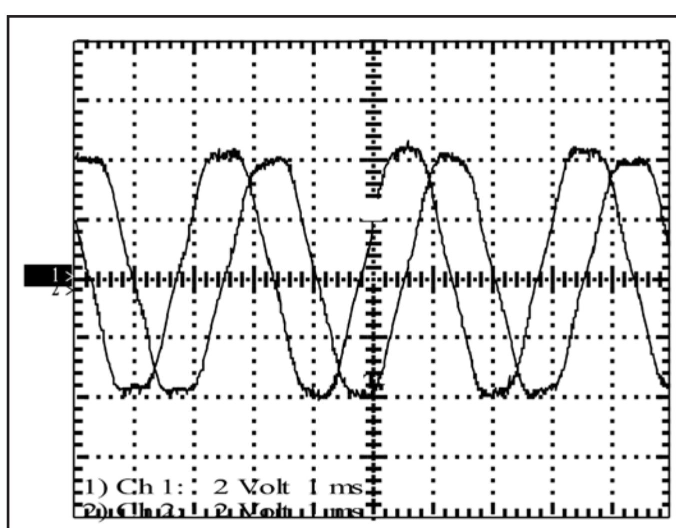


Figure 2 Back-EMF of full step stepping motor.

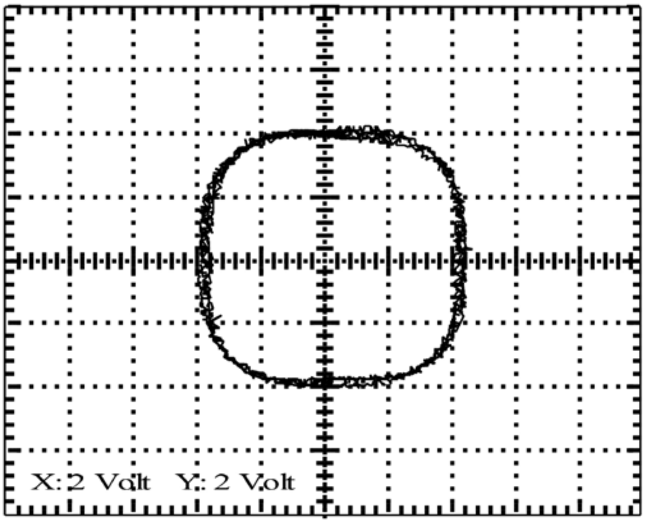


Figure 3 Back-EMF full step in phase plane.

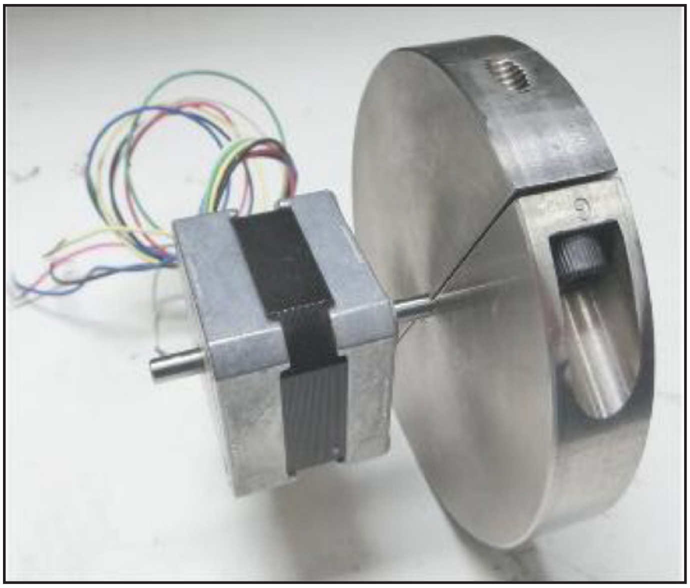


Figure 5 Motor with large flywheel.

in torque when this motor is excited sinusoidally—either microstepping or closed loop.

If the oscilloscope has the capability, or an offline calculation is used, a chart of the harmonic content can be obtained (Fig. 4). The backEMF of a full stepping motor shows large 3rd and 5th harmonic content, resulting from the squaring of the waveforms due to the design of the rotor and stator teeth.

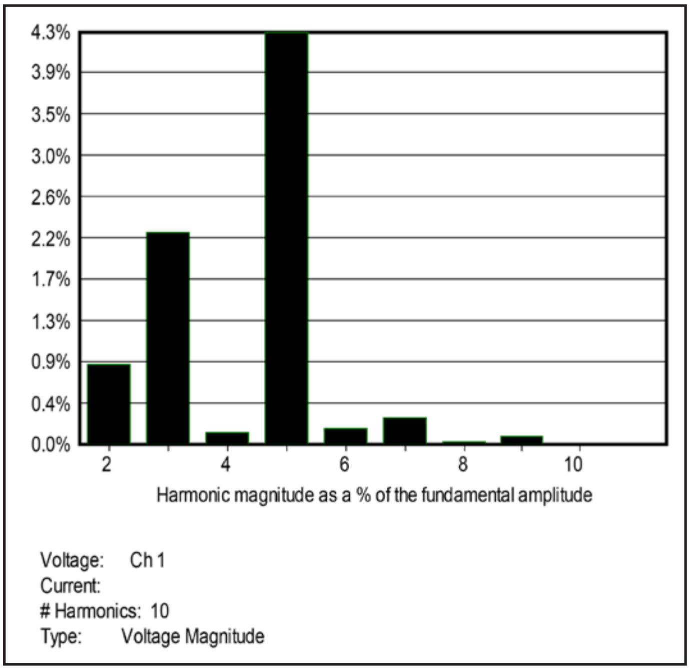


Figure 4 Harmonic content—full-step motor.

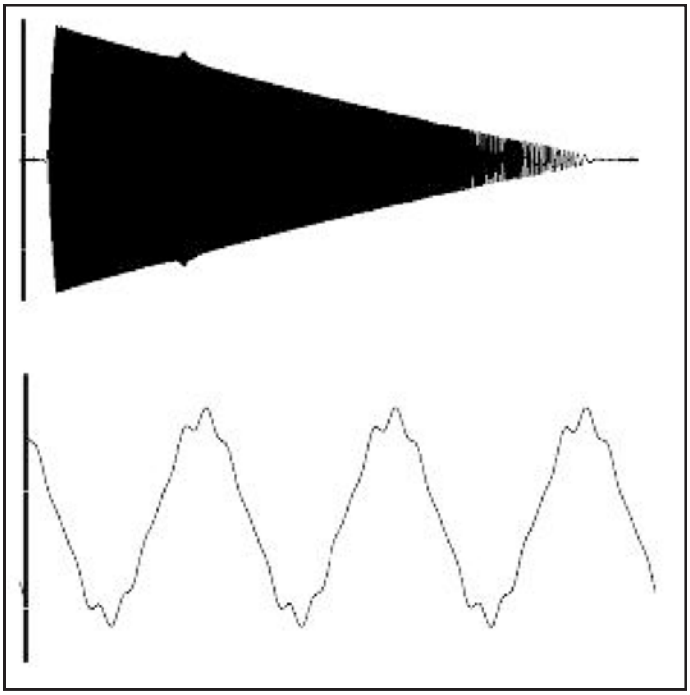


Figure 6 Waveform with blip.

Visualizing Detent Torque

Detent torque—both magnitude and harmonic content—can be easily viewed by attaching a large flywheel (Fig.5) to the motor being tested. One of the windings is connected to a storage scope, i.e.—a digital scope with deep memory—including USB oscilloscopes shown here—work well. The motor body is secured, and the flywheel is spun up by hand and allowed to slow down on its own. For the full stepping motor shown, a blip about 25% from the peak speed is visible in the top waveform of Figure 6. Expanding the blip, it appears that the 5th harmonic of the main waveform is present. The large flywheel does not significantly change its speed at the pulse rate of the detent torque, but the motor inertia and the spring of the shaft form a mechanical resonance that will resonate when the frequency of the detent torque—or one of its harmonics—hits the resonance frequency. The friction in the system gradually slows the flywheel, scanning the various frequencies. Additional harmonics may be seen if the detent torque versus angle is very steep. Lower harmonics require higher speeds to resonate. (You may need a string around the wheel like a pull start lawn mower to reach these speeds.) This sharp shape of detent may also be detected by rotating the un-energized motor by hand; the motion feels like a series of detents.

Micro-Step Design

The *micro-step optimized motor* originated as a smoother version of the 2- phase sinusoidal drive using a split phase capacitor for the second phase, as shown in US2982872 in the first article in this series. Other variations to optimize smooth motion are shown in multiple patents, involving changes in the pitch, position, and width of the stator teeth versus the rotor teeth, such as are shown in US7518270. Figure 7 shows a tooth configuration also known as 48:50 tooth spacing with 6 teeth on the stator claw (top) spaced at a wider spacing than the rotor teeth (bottom) such that they do not all come into alignment simultaneously. These styles of motors are preferred for both micro-stepping and for closed loop applications.

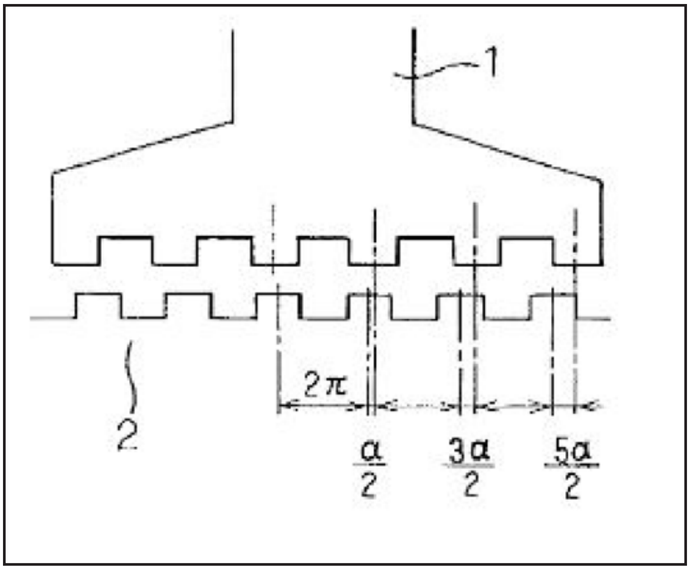


Figure 7 48:50 micro-step laminate.

The micro-step-optimized motors produce a much more sinusoidal back-EMF, as is visible in both the time and phase plane charts. The radius is nearly constant, producing nearly the same torque (when sinusoidally driven) for all angles of rotation. This motor shows significantly smaller third and fifth harmonic content in its back-EMF (Figs. 8-9).

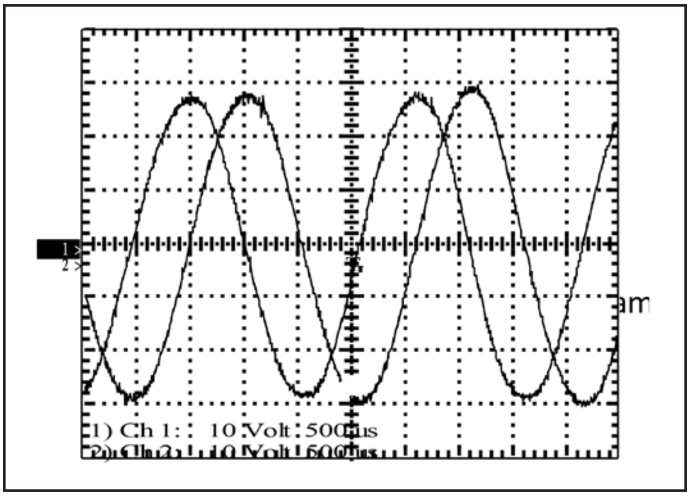


Figure 8 Micro-step back-Emf waveforms.

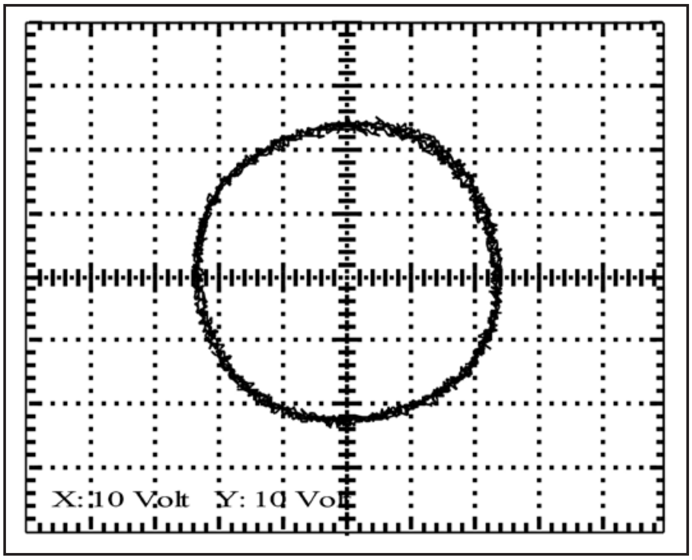


Figure 9 Back-EMF waveforms in phase plane for micro-step.

The un-energized detent torque is greatly reduced in both magnitude and in higher harmonic content for the micro-step optimized motors (Fig. 10). The detent reduction comes about avoiding the simultaneous alignment of many rotor and stator teeth. Careful choices on spacing and the width of the teeth for both the stator and rotor can help to keep the reluctance path much more constant.

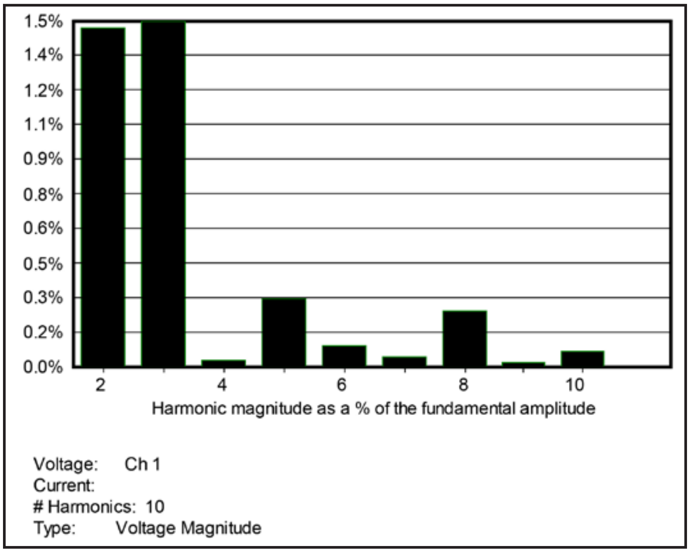


Figure 10 Harmonic content — micro-step.

The flywheel test of the high quality micro step motor design shows a very smooth decay (Fig. 11). The backEMF also appears much more sinusoidal, as expected. The damping friction of the motor can be easily calculated by determining the time to decay for one time constant and calculating the flywheel inertia. This separates the detent torque from the friction.

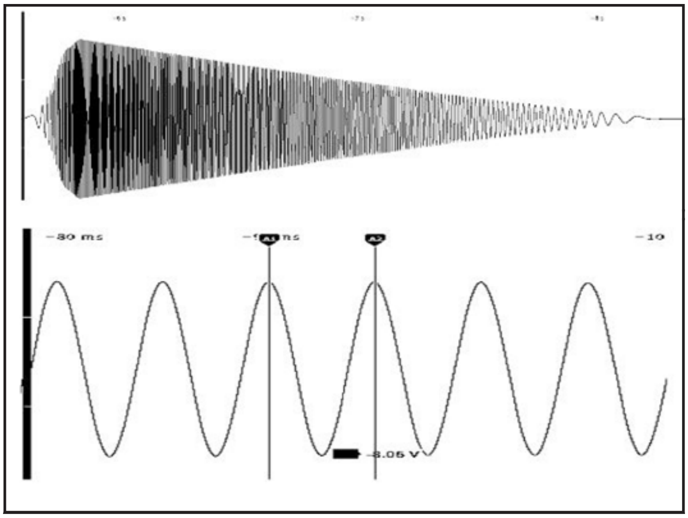


Figure 11 High-quality micro-step motor waveforms.

Measuring Motor Parameters

Spinning the motor at constant speed — such as using a hand drill motor — while measuring the output from the windings can be used to measure the back EMF constant of the motor. When the back EMF is divided by the motor speed in radians per second, the numerical value for *Kv* is the same as for *Kt* in Newton-meters/Amp (assuming a sinusoidal drive). The cycle RMS value for multiple cycles gives a good repeatable measurement. The balance of the motor phases can be easily calculated. Using an oscilloscope with math functions, the product of the two phases can be determined, and the integral of the product can be taken. The integral of sin (*t*)*cosine (*t*) should equal zero when integrated over full cycles. If the phases are not 90 degrees apart, then this integral will be non- zero. This can indicate a dropped motor or mis-manufactured motor.

The inductance of the motor is also readily measured by adding a resistor across the winding of approximately the motor winding resistance (*Rw*) up to about 10x the winding resistance. The open voltage and frequency (*Vo*, *Fo*) are measured, the resistance (*Rl*) is added across the winding and the loaded voltage and frequency are measured. The open readings are used to determine the *Kv* (backEMF constant). The frequency for the loaded measurements are used to calculate the internal voltage, the internal resistor and inductance drop the voltage, with the current measured via measuring the voltage across the load resistor. The voltage across the internal resistor is readily calculated, and knowing the inductance voltage drop is at 90 degrees to the resistive voltage drops, the voltage across the inductor is easily calculated. Knowing the voltage and current gives the impedance, and knowing the frequency gives the inductance. A drill motor, a resistor, a VOM or oscilloscope than can measure RMS voltage and frequency, and you can measure the motor inductance under significant current load. This is a measurement much more reflective of the inductance as the motor will be operated. The motor windings have significant capacitance to the stator, which can significantly degrade the measurements of many LCR meters; probing with much lower current the capacitive shunt currents can cause bad readings. **PTE**

Vl_int=*Vo*/*Fo***Fl*	(Loaded internal backEMF voltage)
Il=*Vl* / *Rl*	(Current through load)
Vr=*Il* * (*Rl*+*Rm*)	(In-phase or resistive voltage)
Vinductor=(*Vl_int*^2−*Vr*^2)^.5	(Solve the right angle triangle for the voltage across the inductor
Lm=(*Vinductor* / *Il*)/(2**PI***Fl*)	(Impedance over electrical frequency in radians per second)

Donald Labriola P.E. is president at QuickSilver Controls, Inc. He has been working with step motors since high school, and has had these motors operating field-oriented closed loop control since 1984.

don_labriola@quicksilvercontrols.com

Continental

ANNOUNCES R&D EXPANSION IN INDIANA

Continental announced plans today to expand its research and development operations in northeast Indiana, advancing innovative technologies to reduce noise vibrations for the automotive and commercial sectors. To support its growth, the company plans to create more than 45 new jobs by the end of 2023.

"Continental's decision to expand in DeKalb County continues a long-standing trend of German companies picking Indiana for growth," said Indiana Secretary of Commerce Jim Schellinger. "With operations all around the world, we're grateful that Continental is choosing to grow in northeast Indiana, developing innovative products that are used across the globe while providing quality career opportunities for Hoosiers."

Germany-based Continental, a manufacturer and distributor of rubber products for a variety of applications, plans to invest more than $4 million to grow its ContiTech Vibration Control business unit in DeKalb County, renovating and equipping a facility at 207 S. West. St. in Auburn. The 100,000-square-foot building will accommodate the consolidation of existing technical centers in Canada and Michigan, while supporting the company's efforts to increase efficiencies in its anti-vibration systems. Continental plans to be fully moved into the facility by the end of 2024.

Continental operates more than 80 locations and employs approximately 46,000 workers across North America, including roughly 470 across its multiple Indiana locations. To support its northeast Indiana growth, the company will begin hiring for positions in testing, prototype, design and product development. Interested applicants may apply online.

"We are excited and grateful about this opportunity to grow in the region," said Scott Bykowski, head of research and development for vibration control technology and noise insulation for Continental North America. "Thank you to the Continental management team as well as state and local governments in Indiana for their strong partnership and support throughout this process."

Continental specializes in vibration control technology and noise isolation for the automotive industry, developing products and systems to optimize in-car vibration and noise levels as well as sealing systems for applications in chassis, brakes and steering. In 2019, the technology company acquired its Auburn location from another major automotive manufacturer. The facility has a long history in the community dating to 1896 when it was operated by Auburn Rubber Corp. Continental operates production sites as well as development and application engineering centers for its vibration control technology and noise insulation solutions in Brazil, China, France, Germany, India, Mexico, Slovakia and the U.S.

"The City of Auburn is excited and very thankful to Continental and its leadership team for selecting our community for this consolidation," said Auburn Mayor Michael Ley. "This investment can be seen as an extension of the lineage of the Auburn Rubber Company. We welcome them to our community!"

The Indiana Economic Development Corporation (IEDC) offered the company up to $650,000 in conditional tax credits based on its plans to create up to 46 new jobs in Indiana. These tax credits are performance-based, meaning the company is eligible to claim incentives once Hoosiers are hired. The city of Auburn approved additional incentives at the request of the DeKalb County Economic Development Partnership.

Indiana is home to more than 1,000 foreign-owned business establishments like Continental, which support more than 203,000 quality jobs. Germany is Indiana's second-largest source of foreign direct investment, with approximately 120 Germany-based companies employing more than 15,100 Hoosiers. (*www.continental.com*)

EASA

ANNOUNCES 2020–2021 OFFICERS AND EXECUTIVE COMMITTEE

The Electrical Apparatus Service Association (EASA) has announced its new international officers for the 2020–2021 administrative year. The new officers are:

- Chairman of the Board: Jerry Gray of Sloan Electromechanical Service & Sales in San Diego, California
- Vice-Chairman: Tim Bieber of D-Electric, Inc. in Quakertown, Pennsylvania
- Secretary/Treasurer: Sid Seymour of Seymour-Smith Electric Motor & Pump Service, in Burlington, Ontario, Canada

Left to right are Sid Seymour (secretary/treasurer), Jerry Gray (chairman of the board), and Tim Bieber (vice chairman).

Chairman Gray has more than 40 years of experience in the electrical apparatus industry. He previously held every elected office in EASA's Southern California Chapter and was director of EASA Region 7. He has served on numerous EASA International Committees, including the Marketing & Industry Awareness, Technical Education and Engineering committees.

Serving on the Executive Committee with the above officers are Immediate Past Chairman Brian Larry of Larry Electric Motor Services, Ltd. in Peterborough, Ontario, Canada; Sean McNamara of Komatsu in Rutherford, New South Wales, Australia; and Paul Rossiter of Energy Management Corp. in Salt Lake City, Utah. *(www.easa.com)*

Timken

INTRODUCES CHAIN ENGINEER WEB APP

The Timken Company has unveiled a new mobile app from Drives featuring a collection of robust tools that make it simple and convenient to find the right chain for new and existing drive or conveyor applications. Called Chain Engineer, the app allows engineers and maintenance professionals to select, interchange, configure and track elongation from their desk or mobile device.

"We are constantly striving to make it easier for our customers to find the best fit for their application needs, which is why we developed this app," explained Rich Neuhengen, principle product manager, Drives. "This chain-focused app not only helps users find the right fit within our product portfolio, but it also allows them to manage the critical maintenance task of tracking elongation on a variety of equipment ranging from cranes and container handlers to industrial drives, conveyors and kiln driers."

Additional features and benefits of the Chain Engineer app include:

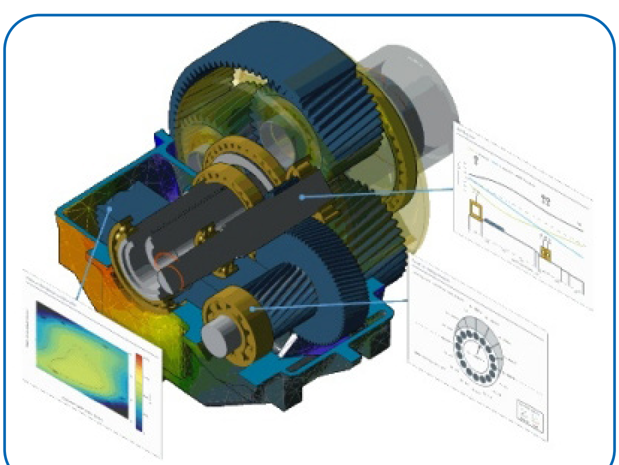
- Drive chain selection: Select a precision roller chain for drive applications based on required parameters and center distance. It can also help confirm whether the right chain is being used in existing applications.
- Conveyor chain selection: Select the ideal conveyor chain for a horizontal, incline or vertical system, including slat, bulk and bucket systems.
- Precision roller chain and attachments interchange: Compare and interchange tier-one chains and attachments.
- Chain measurement: Provides instructions on how to measure leaf chain, roller chain, agricultural chain and kiln drier chain. Allows user to input data and track chain wear life on various applications. Users can continue to record data and access and share reports under their established accounts, supporting maintenance best-practices over the life of their equipment.
- Chain configurator access: Visually see your chain assembly as you choose your specific size, length and attachments. Generate 2D or 3D CAD modules, submit a request for quote and ensure proper communication of your drive requirements.
- Resource library: Access a library of helpful technical documents, brochures, catalogs and more.
- Save and share feature: Create reports and download PDF files that can be easily shared with customers or colleagues.

Chain Engineer is a mobile web app and can be downloaded to your phone by using the "save to home screen" or comparable feature available on your device. Chain Engineer is also available as a web-based resource at ***www.chain-engineer.com***. Also available, the Drive Engineer belt drive design web app from Timken Belts can be accessed via a link on Chain Engineer. (*www.timken.com*)

FVA GmbH

OFFERS BASICS OF GEARBOX DESIGN ONLINE SEMINAR

FVA GmbH presents a live online seminar on "Basics of Gearbox Design: Requirements, Concept and Design," on November 13, 2020 from 10:00–11:30 Uhr. Fundamental properties of a gearbox, like load capacity and NVH behavior, can be positively influenced already in a very early stage of gearbox development. This seminar imparts the knowledge of sizing the most important gearbox components in general and answers the following questions in detail:



What are the most important requirements to be defined when starting a new gearbox design and how is the design affected when these requirements are changed?

How are the most important components like gears, shafts and bearings sized and how can they be optimized regarding load capacity and NVH?

What is to be regarded in the first rough housing design?

How can size and weight of the gearbox assembly be estimated already in a very early phase of design?

The speaker for the event is Prof. Dr.-Ing. Markus Klein, University for Applied Sciences Munich, machine elements and engineering design. (*register.gotowebinar.com/register/2313761000736756239*)

Motion Industries

ANNOUNCES TWO ACQUISITIONS

Motion Industries, Inc., has announced two acquisitions. Motion has entered into agreements to acquire TRC Hydraulics, a Canadian-based supplier of hydraulic products and services, and F&L Industrial Solutions, Inc., a distributor of T-slotted aluminum extrusion components. Both transactions closed with an effective date of August 1, 2020.

In business since 1986, TRC Hydraulics has served the Atlantic Canada region with several full-service sales and repair facilities in Canada. In 2019, TRC Hydraulics expanded by opening a facility near Spartanburg, South Carolina.

Along with distributing many lines of hydraulic product, TRC designs, manufactures, and maintains hydraulic components and systems. TRC also engineers customized hydraulic and mechanical solutions, and offers the additional services of experienced fabricators, welders, machinists, and hydraulic technicians.

"This is a fantastic opportunity to grow our business with a leading company that shares the same core values as we do," said TRC President and CEO Terry Coyle. "We look forward to leveraging the many resources that Motion Industries offers and enhancing our services to provide greater value to our customers."

Based near San Diego, California, F&L Industrial Solutions has served the southwest U.S. with full-service aluminum extrusion components since 2002. F&L offers local inventory including the 80/20 brand of aluminum, an experienced staff of CAD designers, in-house machining, digital panel cutting, full assembly/manufacturing, on-site delivery, and installation. Custom-designed products include a wide array of enclosures, clean rooms, walls, platforms, cabinets, racks, sneeze guards, tool holders, electrical connections, robotics, specialized carts, and more.

"It's a perfect fit of our analogous visions and business cultures," said F&L Industrial Owner, Mike Fanolla, who co-founded F&L. "We look forward to the growth opportunities, and with us joining Motion Industries, our customers can anticipate even greater high-quality service they've come to know from our company."

"We are pleased to welcome these outstanding organizations, TRC Hydraulics and F&L Industrial, to the Motion family," said Motion Industries President, Randy Breaux. "TRC gives us the opportunity to expand our hydraulics business in the Atlantic Canada markets. And with its aluminum extrusion niche, F&L will nicely supplement our Mi Automation Solutions Group. We look forward to working with the talented people of both companies to grow our market footprint and build on our industry-leading position, creating even more value for our customers in the coming years."

Mi Automation Solutions Group offerings to customers include control panels, conveyors, machine vision, motion control, network connectivity, pneumatics, robotics, sensing I/O and other automation-related solutions. (*motionindustries.com*)

Drivetrain Hub

LAUNCHES CONSULTING NETWORK

Drivetrain Hub has launched its web service for matching clients to consultants in the drivetrain industry, known as Consultant Match. Their network of consultants offers a wide variety of engineering services and are capable of delivering advanced solutions for challenging drivetrain projects.

In addition to the matching process, Consultant Match includes web tools that make it very convenient to request quotes, share documents, submit/receive proposals, and manage multiple bids simultaneously. This means major time-savings for both clients and consultants.

Through this process, the client's purchasing team obtains fair quotes that check all of the technical engineering requirements, while providing consultants with an abundance of opportunities.

Consultant Match is the world's drivetrain engineering platform for matching client requirements to consulting services. Find solutions in design, analysis, testing, prototyping, and manufacturing for gears, bearings, motors, and more.

(*drivetrainhub.com/consultants/*)

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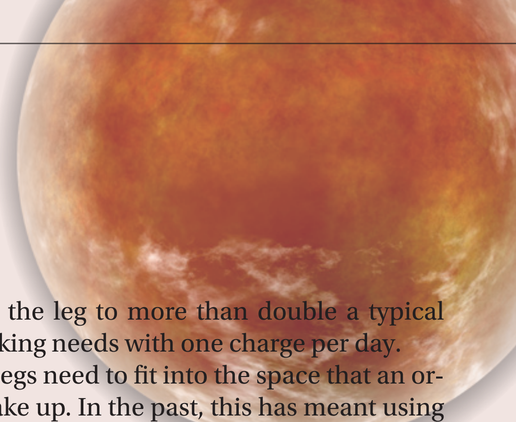


Motors in Space

Edited by Matthew Jaster, Senior Editor

Components like motors, bearings and drives are subject to harsh environments on Earth, but they must be at the top of their game to enjoy space travel. Recent applications from Maxon Motors (Return to Mars) and the University of Michigan (Robotic Legs) illustrate the incredible requirements it takes to handle applications in space and how these components can be utilized here on Earth.

Return to Mars

NASA's Jet Propulsion Laboratory (JPL) asked Maxon to produce 10 drives for its latest Mars rover, Perseverance. For the first time, NASA is using brushless DC motors, including: nine EC 32 flat and one EC 20 flat in combination with a GP 22 UP planetary gearhead. Working closely with JPL specialists, Maxon engineers developed the drives over several years and tested them thoroughly to achieve the highest standards of quality.

"We've learned a lot from this exciting project," says Robin Phillips, head of the Maxon SpaceLab. "We now have very broad expertise in space applications and have established quality assurance processes that meet the expectations of the industry. Customers from other industries such as the medical sector, where requirements are often similar, can also benefit from this know-how."

Space missions place the highest demands on drive systems. This includes vibrations during the rocket launch, vacuum during the journey, impacts on landing, and the harsh conditions on the surface of Mars, where temperatures fluctuate between –125 and +20 degrees Celsius and dust penetrates everywhere. A drone helicopter called Ingenuity is attached to the bottom of the rover and includes six Maxon brushed DCX motors with a diameter of 10 millimeters controlling the tilt of the rotor blades and the direction of flight. The Perseverance rover is expected to land on Mars on February 18, 2021. *Editor's Note: Learn more on page 20.*

Improving Robotic Legs

In a recent article by the communications department at the University of Michigan, scientists created a robotic leg prototype that offers a more natural gait and is more energy efficient than previous designs. The key is the use of new small and powerful motors, originally designed for a robotic arm on the International Space Station. The streamlined design offers a free-swinging knee and regenerative braking, which charges the battery with energy captured when the foot hits the ground. This feature enables the leg to more than double a typical prosthetic user's walking needs with one charge per day.

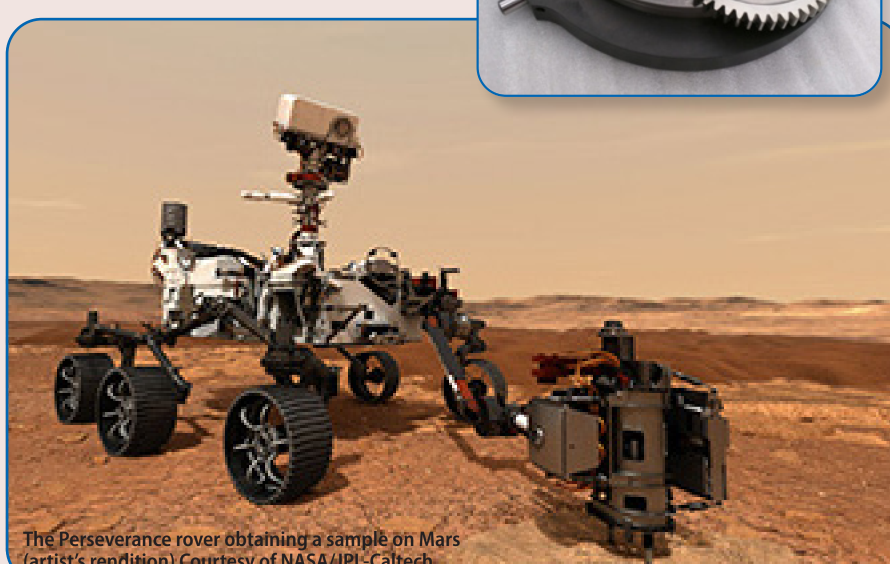
Motors in robotic legs need to fit into the space that an ordinary limb would take up. In the past, this has meant using small motors that spin quickly, and then using a series of gears to convert the fast spin into a more powerful force.

The problem is that the gears are noisy, inefficient, add weight and make it harder for the joints to swing. Robert Gregg, an associate professor of electrical and computer engineering at the University of Michigan and a member of the U-M Robotics Institute, and his group surmounted this by incorporating two of those stronger space station motors, one powering the knee and the other powering the ankle.

There are many benefits to using fewer gears. In addition to enabling the free-swinging knee, removing gears brought the noise level down from the scale of a vacuum cleaner to a refrigerator. Also, the regenerative braking absorbs some of the shock when the prosthetic foot hits the ground. The team's next step is to improve the control algorithms that can help the leg automatically adjust to different terrain, changes in pace and transitions between different types of activity. **PTE**

Learn more here: (*news.umich.edu/space-station-motors-make-a-robotic-prosthetic-leg-more-comfortable-extend-battery-life/*)

With fewer gears, Gregg's team was able to implement a free-swinging knee and regenerative braking to help the leg go all day on a single charge. Photo courtesy of Locomotor Control Systems Laboratory, University of Michigan.



The Perseverance rover obtaining a sample on Mars (artist's rendition) Courtesy of NASA/JPL-Caltech.