August 2011

GEAR TECHNOLOGY

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The Journal of Gear Manufacturing

Feature Articles

- Gear Noise
- Raw Materials
- State-of-the-Art Broaching

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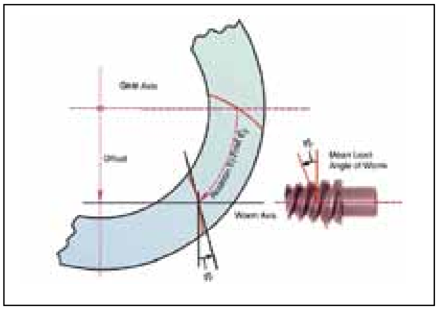
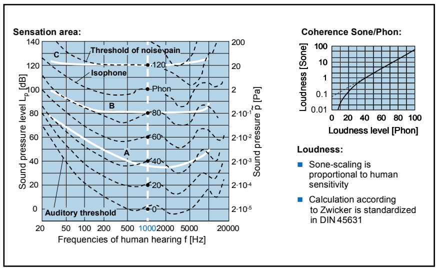


TECHNICAL ARTICLES



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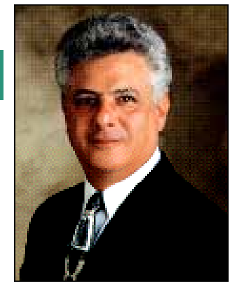

नमस्ते
(Namaste)

In India, "namaste" is used as a common greeting. Although it translates literally to "I bow to you," it's often used the same way we use "hello" or "good-bye." It's a phrase commonly exchanged between individuals when they meet, and it's also used as a salutation when they part. I'm using the phrase here because I'd like to introduce you to an exciting new project and venture for Randall Publications LLC.

In 2012, we will be introducing a new magazine for the Indian marketplace. The magazine, ***Gear Technology India***, is designed for engineers and managers at companies where gears are designed, manufactured, purchased and used. It will be printed and distributed in India.

Gear Technology India will be like a good curry powder—a flavorful blend of spices that all work together to create something new and desirable. But instead of turmeric, coriander and cumin, our recipe will include the same mix of technical and feature articles you're used to, but with a strong measure of local news and information. It will include articles written by Indian authors for the Indian marketplace.

In order to accomplish this, we've enlisted the help of Virgo Publications, the sister company to Virgo Communications and Exhibitions Ltd., which many of you have already come to know. Last year Virgo organized the first International Power Transmission Expo (IPTEX 2010) in Mumbai, and the event was considered a success by both the attendees and exhibitors we've talked to. That event was supported by the AGMA, as well as numerous exhibitors from India and the worldwide gear industry. IPTEX 2012 takes place this February in Mumbai again. That's where and when we'll introduce our new magazine.

We expect this new publication to be extremely well received. Over the years, India has become our largest new source of readership outside the United States. There's a hunger there for the type of information we produce. Of course, there are other technical magazines and newspapers in India, but they serve a broad industrial or engineering marketplace. Indian engineers don't have anywhere to turn for the type of focused technical information we provide.

In fact, at IPTEX 2010, the visitors to the show were surveyed about whether they saw a need for an Indian magazine focused on the gear industry, and the response was overwhelmingly in favor.

So why are we telling you all of this? What does any of this have to do with manufacturing in America? We expect that many of you probably have an interest in India.

Whether you're an Indian company or a non-Indian company, whether you're already doing business there or strongly considering it, global trade has become a fact of life in modern manufacturing. The world has shrunk, and it continues to shrink. ***Gear Technology India*** will provide an advertising venue in one of the largest industrial marketplaces in the world. With 1.2 billion people and a growing middle class, India's manufacturing sector is robust.

We also welcome you to become a subscriber to the new magazine. It will be printed and distributed physically in India, but the electronic version will be available to all. Even if you have just a passing interest in doing business there, a subscription to ***Gear Technology India*** will keep you abreast of what's happening on the sub-continent.

Finally, if you have stories you'd like to share with us, or if you'd like to contribute articles to ***Gear Technology India***, we'd love to hear from you. Send a note to ***publisher@geartechnology.com.***

Until next time, namaste.

Michael Goldstein,
Publisher & Editor-in-Chief

Arrow Gear Expansion

SUPPORTS AEROSPACE PROJECTS

Arrow Gear is supplying gears for the CH-53 Super Stallion (courtesy of Air Force Master Sgt. Dawn M. Price).

A gunner aboard the CH-53 Super Stallion watches another helicopter take off (courtesy of Air Force Master Sgt. Dawn M. Price).

Presented with an opportunity from Sikorsky to supply several gears for a Blackhawk helicopter project, Arrow Gear did not have the required equipment capable of accommodating the large Sikorsky internal ring gear. At that point, Arrow's maximum capacity for spur gears was 22" and the Sikorsky parts would require up to a 36" capacity. If the company was interested in taking on the project, it would require a multi-million dollar expansion.

Around this time, another opportunity for Arrow presented itself in the form of the CH-53 Super Stallion, also produced by Sikorsky. The new "K" version of the CH-53 had been developed, in part, for military operations in the mountainous regions of Afghanistan. The previous version was unable to carry a full payload over the tops of the Afghan mountains.

The new "K" version is a significant improvement to this supply and transport aircraft. Equipped with the latest technology, the "K" version can fly three times higher and three times farther without refueling. This enhanced ability provides numerous strategic benefits to military personnel operating in this part of the world and will help to save lives of U.S. war fighters.

Arrow was approached by Sikorsky to produce prototype bevel gear sets to be used in the Super Stallion's three gearboxes. Notably, this project called into play Arrow's advanced gear design technology. Using tooth contact analysis (TCA) and finite element analysis (FEA), Arrow was able to work with Sikorsky on refining the development of the gear tooth design and predicting tooth contact performance under load. But again, the issue of size capacity to actually manufacture all the gears remained a problem.

"In the face of these opportunities, Arrow's chairman and CEO, James J. Cervinka, made the difficult decision to borrow the money required for the upgrade to accommodate larger gears for the Blackhawk and Super Stallion programs," says Joseph L. Arvin, president of Arrow Gear, adding, "an investment that came to approximately $4.5 million."

Key components of the expansion included the purchase of a Höfler Helix 800 spur and helical grinder, a Gleason Phoenix II # 600 spiral bevel grinder, a Gleason Phoenix II # 275

continued

spiral bevel grinder, two Gleason # 450 HC Phoenix gear cutters, a 36" CNC Doosan vertical turning lathe, a 36" CNC vertical surface and OD/ID grinder, a 36" DixiTech CNC quench press with specialty tooling, a Zeiss 36" x 70" CMM inspection machine, a large Magnaflux machine and a substantial expense for the tooling required for machining and inspecting the workpieces.

The last of these new additions were recently implemented. As a result, Arrow Gear will be producing gears for the Blackhawk and CH-53K projects. "In the end, this investment allowed Arrow to substantially increase production capability," Arvin adds, "Now, instead of 22" (558.8 mm) parts, Arrow can produce parts up to 36" (914.4 mm).

For more information:
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2301 Curtiss St.
Downers Grove, IL 60515
Phone: (630) 353-9260
www.arrowgear.com

MAG

Demonstrates Five-Axis Machining Center at imX

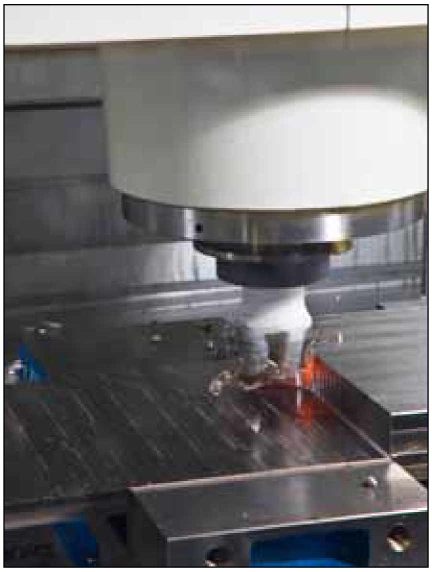
MAG's modular HMC 1250/1600 Series will be demonstrated at the Interactive Manufacturing Experience (imX) show with cryogenic tool cooling technology and a new cryogenic-equipped A-axis tilt-spindle for five-axis horizontal machining on large parts. The imX demo, which supports MAG's Learning Lab on cryogenic machining, will feature parts of titanium, compacted-graphite iron (CGI) and composites. The imX takes place September 12–14 at the Las Vegas Convention Center.

The HMC1250/1600 Series is engineered for high-precision, high-productivity machining of large aerospace, power generation, pump, valve and off-road equipment parts. It now includes six spindle options to suit special-purpose or general machining requirements. The new 6,000 and 8,000 rpm/46-kW (61.6 hp) tilt-spindle—with + 90/–120 degree A-axis travel—joins an all-around 10,000 rpm/56-kW (75 hp) spindle, high-speed 24,000 rpm spindle, high-torque 2,600 Nm/80-kW (1,918 ft-lb) spindle and two live spindles (110 or 130 mm diameter). The high-torque spindle is especially suited for hard-metal cutting, while the live spindles extend W-axis reach by up to 800 mm (31.5 in), enabling deep cavity milling to high precision with shorter, more rigid tool lengths. Standard on the live spindle, MAG's exclusive Z-axis thermal compensation software dynamically offsets spindle growth to maintain tight tolerances.

Designed for extreme application flexibility, the HMC 1250/1600 offers maximum 3,000 mm (118 in) work-zone swing, 2,500 mm (98.4 in) work-height capacity and 15,000 kg (33,000 lb) pallet load capacity. Major machine components, including the X-bed, Z-bed and column, are cast ductile iron, with pallets up to 1,600 x 2,000 mm, headstock and rotary table housings of gray cast iron. Modular design provides a range of machine travels, 60- to 300-tool magazines and two control choices.

Powerful and agile, the new HMC offers 56 to 80 kW (75 to 107 hp) spindle power, 35 kN (7,870 lb) Z-axis thrust, and super-rigid, full-contouring hydrostatic rotary table. The 360,000-position contouring table provides a rigid work platform, while a rugged worm gear drive with clamp securely holds axis position. Rotary table positioning accuracy is 10 arc seconds, repeatable to five arc seconds. Positioning accuracy of the tilt-spindle is 4 arc seconds, repeatable to two arc seconds.

Meeting industry needs for tighter part tolerances and greater machining accuracies, the HMC Series comes standard with linear scale feedback in X, Y and Z axes, providing 8 micron (0.0003 in) positioning accuracy and five micron (0.0002 in) repeatabili-



ty. Heavy-duty hardened and ground roller guide ways enable a rapid traverse rate of up to 40 m/min (1,575 ipm) with high acc/dec rates, double the load capacity and nearly 10 times the wear life of ball-type ways. The full work zone enclosure is pre-engineered for dust collection with dry LN2 machining, and includes a doorway for operator access with walkway/platform inside.

For more information:
MAG IAS
142 Doty Street
Fond du Lac, WI 54935
Phone: (920) 921-9400
Fax: (920) 906-2522
www.mag-ias.com

Cimcool 609

DESIGNED FOR GRINDING PERFORMANCE

Cimcool Fluid Technology has created Cimtech 609, an innovative hybrid developed for superior grinding performance and excellent machining ability. Designed for moderate-to-heavy-duty operations, Cimtech 609 is a suitable metalworking fluid concentrate for most aluminum alloys, titanium, exotic alloys, cast iron, carbon steels, high speed steel, high alloy steels and stainless steels, and is applicable for some stamping and drawing operations. Cimtech 609 offers lubricity with a grinding ratio that exceeds that of most chlorinated

continued

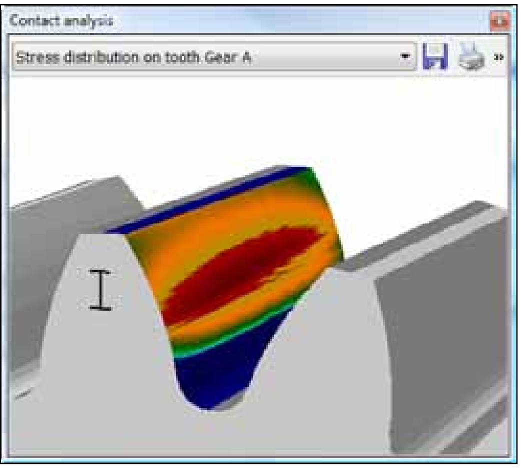
soluble oils, without using chlorinated extreme pressure additives, and is proven for bearing, valve stem and other difficult grinding operations with close tolerance requirements. It can also be used to form tap most aluminums, has excellent drawability, and—with its biological protection—can be considered for use in recirculating systems. Cimtech 609 also offers excellent cleanliness, minimal residue and excellent microbial control for long sump life. Its specialized corrosion inhibitors allow for the use of this product on both ferrous and most non-ferrous applications and it is compatible with titanium and other exotic alloys. Cimtech 609 is also operator friendly, with no smoke, low misting and no slippery film on parts, machinery or floor.

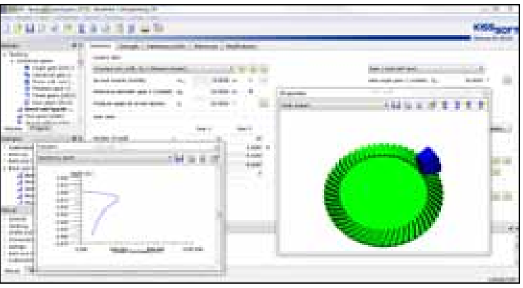
For more information:
Cimcool Fluid Technology
3000 Disney St.
Cincinnati, OH 45209
Phone: (888) 246-2665
www.cimcool.com

KISSsoft Updates

INCLUDE CONTACT ANALYSIS, SINTERED MATERIALS AND FLANK BREAKAGE

KISSsoft has continued releasing updates to its *03/2011* software release including new material on contact analysis, sintered materials and flank breakage. In the contact analysis of *KISSsoft*, the effects of shaft deformations may now be precisely evaluated (module *ZA30*). The results of shaft calculations can also be directly imported to the contact analysis. Bending and torsion of shafts are furthermore calculated load-dependent





and considered in the tooth contact. In the *KISSsys* calculation, the shaft classification is done automatically. Additionally, the face load factor KHβ is calculated according to ISO 6336-1, Annex E. Another new feature is to combine the profile and lead correction factor within defined areas. Thus all variants are automatically analyzed in respect of the load distribution, transmission error, safety against micropitting, wear and flash temperature and the stress curve (module *ZA33*). The pressure curve and root stresses are currently shown on the flank of the gears as well, allowing a direct comparison with the contact pattern on the gear during the assembly, operating process and test rig. All these features constitute a huge improvement of the gear calculation under load for planetary gears and cylindrical gear pairs.

The Swedish company Höganäs AB provided the *KISSsoft* calculation program with SN-curves for tooth bending of sintered material Distaloy AE. Two different conditions were measured: The case hardened (0.2 percent C and 0.8 percent C-potential) and the through hardened (0.6 percent C) ones. The fatigue data was extrapolated to one percent risk of damage as requested by ISO 6336 standard. There is no information in ISO 6336 or DIN 3990 for the calculation of sintered materials. But as Höganäs provided complete Woehler-line data, which can be read and used by *KISSsoft*, the life factor YNT for bending is calculated based on the real SN-curve. Therefore bending strength calculation according to ISO 6336 is possible. The Distaloy

continued

materials will be fully integrated in the gear material database of the 2012 release. For the *KISSsoft Release 03/2011*, the data is now available on request.

The flank breakage of gears is a failure mode that is separate from the damage forms such as root breaking or pitting. Consequently, it adds a further risk factor for gearbox failure. To be able to calculate this damage form in advance, extensive studies were performed on spiral bevel gears by Dr. Annast at the FZG Munich. On the basis of this analysis, the flank breakage calculation for bevel gears, and additionally for cylindrical gears, was implemented in the current *KISSsoft Release 03/2011 (module ZZ4)*. Thus, a reliable risk assessment of flank breakage and its calculation is now available for the user.

For more information:
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CH-8634 Hombrechtikon
Switzerland
Phone: +(41) 55 254 20 50
www.kisssoft.ch

Nikon Metrology

PROVIDES LATEST INSPECTION CAPABILITIES

Nikon Metrology introduces the HN-6060, a next-generation non-contact inspection system providing the latest in metrology capabilities. With advanced laser scanning, five-axis synchronized hardware control, ultra-stiff design and powerful processing software, the HN-6060 allows for fast, ultra-precise inspection of complex shapes. This includes gear teeth, turbine blades, appliance housings and much more.

"The HN-6060 multi-sensor system builds upon the Nikon Metrology portfolio of vision systems and 3-D solutions," says Myles Richard, managing director of Americas for Nikon Metrology. "It addresses the need for fast, high-accuracy 3-D inspection of complex shapes by combining innovative optical technology with the highest precision measurement hardware." The newly designed laser scanning sensor extracts the surface form and waviness data in one scan. Previously, tactile gear-inspection tools needed to rely on 2-D sections of data. This new advancement provides better inspection possibilities, revealing all shape and waviness information in one simple measurement.

"What the HN-6060 provides is a much easier, quicker and more precise method of 3-D data capture than metrology systems have demonstrated before," says Robert Wasilesky, senior vice president of sales for Nikon Metrology. "The demand for high-accuracy 3-D surface metrology systems continues to increase as the automotive, aerospace and appliances industries also implement higher precision."

The metrology system's laser scanner and SFF (shape from focus) sensor use active texture projection to perform high-precision measurement of shapes even with glossy surfaces or no surface texture. Touch probes and optical heads with built-in TTL laser AF complete the multi-sensor system. This allows it to perform shape measurements of parts such as complex automotive and machined components, molded parts, and medical devices.

Another core element of the HN-6060 is its five axes of synchronized hardware control. This allows optimum part orientation to the sensor and can measure the part from dif-

continued

ferent angles. The HN-6060 software integrates with the measurement hardware and is designed for user operability and safety. It features macro-based teach in, simulation for collision avoidance, easy acquisition of point clouds from 2-D and 3-D shapes, and insightful part-to-CAD comparison.

For more information:
Nikon Metrology, Inc.
12701 Grand River Avenue
Brighton, MI 48116
Phone: (810) 220-4360
www.nikonmetrology.com

Iscar

LAUNCHES HPC CUTTING TOOLS

For the first time, a complete line of standard tools for high pressure coolant (HPC) turning puts more efficient turning of titanium, Inconel and stainless steel within easy reach of any shop. Previously, HPC tooling was available only as a special. Manufacturers can now get the same quick delivery and security of supply for HPC tools as for any standard tool. In combination with optional standard high pressure plumbing readily available on virtually all mainstream turning machines, Iscar JETHP (jet high pressure) tools bring three key benefits on these problematic metals— they consistently end chip jamming, and improve tool life more than 10 to 1, while doubling removal rates.

HPC turning has been proven effective for decades as a stable, safe process, especially on titanium. The obstacle has been that it required custom coolant plumbing and special tools. More recently, most machine builders have made high-pressure coolant plumbing capability a standard option. Iscar has completed the HPC chain by standardizing the tooling as well and making it as easy to use as regular tooling. The Iscar JETHP family covers the full range of turning, grooving and parting tools and includes HPC versions of the company's Isoturn, Heliturn, Tang-Grip, Pentacut and Cut-Grip tools, in both standard and interchangeable-tool Camfix styles. Their design derives from more than a decade of Iscar experience in supplying special HPC tooling to hundreds of manufacturers, mostly titanium fabricators.

All styles feature internal coolant paths compatible with through-spindle plumbing in the machine. The JETHP line also includes all connection accessories as standard. HPC turning works by aiming a high pressure "hydraulic wedge" of liquid coolant precisely into the cutting zone, shattering chips into uniformly small, classic C-shapes and ejecting them completely. In addition, because it remains liquid at such high pressures and flow rates, it lubricates and cools the cutting area more effectively. Between 40 and 400 bars pressure, the higher the pressure, the smaller the chip in titanium, Inconel and long-chipping stainless steels.

In the Iscar Isoturn line, two separate streams simultaneously deliver coolant to the top rake and bottom flank of the tool. The nozzle for the top stream can be aimedand is easy to move out of the way for convenient insert indexing and replacement. It automatically snaps back into place when coolant is turned back on. The bottom stream can be turned on to enhance the cooling effect. Other models in the line have discharge points, always targeting the cutting zone.

For more information:

Iscar Metals Inc.
300 Westway Place
Arlington, TX 76018
Phone: (817) 258-3200
www.iscar.com

Riten Live Centers

ENGINEERED FOR SMALL WORKPIECES

Riten Extra-Light live centers are designed specifically to turn or grind parts weighing as little as two ounces. These parts are commonly found in the medical and aerospace industries, as well as the manufacture of small engine components. Parts of this

continued

size are often too light or too flimsy to turn the larger bearings found in typical live centers. This is a common problem, resulting in galling or excessive wear on the tip of the live center and/or damage to the part when the center fails to turn with the part. The Extra-Light live centers can turn parts at speeds up to 8,000 rpm while holding concentricity of ± .00005". This is achieved by using miniature precision angular contact bearings graded and matched at the factory to obtain the proper fit necessary to hold concentricity in high rpm applications. The small bearing head diameter and long

spindle provide exceptional clearance for small workpieces, making the center an excellent choice for high production machine tools running light parts. Available from stock in 1, 2, 3 and 4 Morse Tapers, with customized designs quickly quoted by using the "Design Your Own" feature found at the website.

For more information:
Riten Industries
1100 Lakeview Avenue
Washington Court House, OH 43160
Phone: (740) 335-5353
www.riten.com

Kistler

INTRODUCES TYPE 5630M SERIES

Kistler, a worldwide supplier of precision sensors, systems and instrumentation for the dynamic measurement of pressure, force, torque and acceleration, has introduced the Type 5630M Series of high-performance process data collectors, designed to offer manufacturers and OEM machine builders with enhanced manufacturing data storage, process visualization and long-term analysis capabilities.

Manufacturers have long used statistical process control (SPC) and statistical analysis to ensure predictability, conformity and waste reduction, as well as to find simple solutions to complex problems. With increasing customer-driven process monitoring demands, simple data collection and analysis are no longer enough. Long-term data storage, as part of the collection process, must also be incorporated to maintain appropriate documentation confirming that a product conforms to a given process. The ability to view data or reproduce the event and analyze that process long after it has occurred becomes an invaluable tool.

With technology developed in collaboration with some of the world's leading engine manufacturers, the new Kistler Type 5630M Series was developed to include all processes that a customer would need for long-term viewing. By assigning a unique part or serial number to each data file, a user can quickly search, locate and view all historical process data. The part search screen, or dashboard, can be user-customized to display an image of the component, allowing for a clear visual representation of the process, as well as the interactive capability for the user to select the area or process portion that the engineer wishes to view. The Type 5630M Series also offers a statistical process analysis module, which allows the user to select a specific manufacturing application, along with an associated date range, to display various statistics, including mean values, standard deviations, six-sigma statistical measurements of Cp and Cpk, and others, within a single screen view.

Kistler Type 5630M Series software is designed for compatibility with most Microsoft Windows operating systems to allow easy connectivity to IT infrastructure, with the added capability to back up data and ensure compliance with various IT software requirements. The unit is placed on an industry-proven industrial PC and can be ordered with a free-standing NEMA 12 enclosure. A standard 115 V power supply source is required for operation.

For more information:

Kistler Instrument Corp.
39205 Country Club Drive
Discovery Centre, C-20
Farmington Hills, MI 48331
Phone: (248) 489-1090
www.kistler.com

Chiming in on Gear Noise:

THREE EXPERTS HAVE THEIR SAY

Jack Mc Guinn, Senior Editor

It is said that "The squeaky wheel gets the grease."

Ok, but what about gear noise?

We talked to three experts with considerable knowledge and experience in this area: Dr. Donald R. Houser—founder and professor emeritus of the Gear Dynamics and Gear Noise Research Laboratory at Ohio State University; University of Cincinnati Professor Teik C. Lim—elected Fellows of ASME and SAE, recipient of the Chang Jiang Chair Professorship awarded by China's Ministry of Education and a major contributor to studies addressing the dynamic analysis and development of precision machine elements including gears, bearings and drivetrains, with applications to automotive, aerospace and manufacturing systems; and Bill Mark, Ph.D., senior scientist–Drivetrain Technology Center–Applied Research Laboratory and Professor Emeritus of Acoustics at Pennsylvania State University.

Dr. Donald R. Houser, founder and professor emeritus, Gear Dynamics and Gear Noise Research Laboratory at Ohio State University (courtesy OSU).

For starters, what is gear noise? It is much more than an "I know it when I hear it" response.

"Gear noise depends a lot on the users and their applications," says Houser. "However, I like to break gear noises into three categories: gear whine—a tonal noise that usually comes from excitations at the gear mesh; gear rattle—a clattering sound that is usually excited by the driving source (such as the internal combustion engine) or loading device; and gimmick sounds—in which I lump things like the effects of nicks, plastic gear screeching, etc."

"Gear noise—often called gear whine—is the unwanted sound produced by the gear meshing teeth action," Lim states. "It is typically harmonic or tonal in nature and occurs at the mesh frequencies that are defined as the integer multiples of the gear rotational speed times the number of teeth. Gear noise is often a result of dynamic mesh force induced by transmission error and other meshing related excitations. Gear noise is often radiated off a structural surface that is excited by gear vibratory energy transmitted structurally from the gear pair to the exterior housing or connected structures. Gear noise is not desirable because it is annoying and conveys poor design and manufacturing qualities."

"This sound can be 'displayed' in the time domain or in the frequency domain. If the meshing gear pair is operating at constant speed and transmitting constant loading or torque, this sound can be displayed in the frequency domain as the super-position of two sets of harmonics—one set of harmonics from each of the meshing gears

continued

of the pair, says Mark. "Each gear of the meshing pair has its own period of rotation and, therefore, its own fundamental frequency, which is the reciprocal of its period of rotation. The frequency harmonics from each of the two gears are integer multiples of the fundamental frequency of that gear of the pair. These harmonics are the rotational harmonics of that gear. If a gear has N teeth, then the Nth rotational harmonic is the tooth-meshing fundamental harmonic. Because of the way two gears mesh with one another, the tooth-meshing harmonics of both gears of a meshing pair coincide."

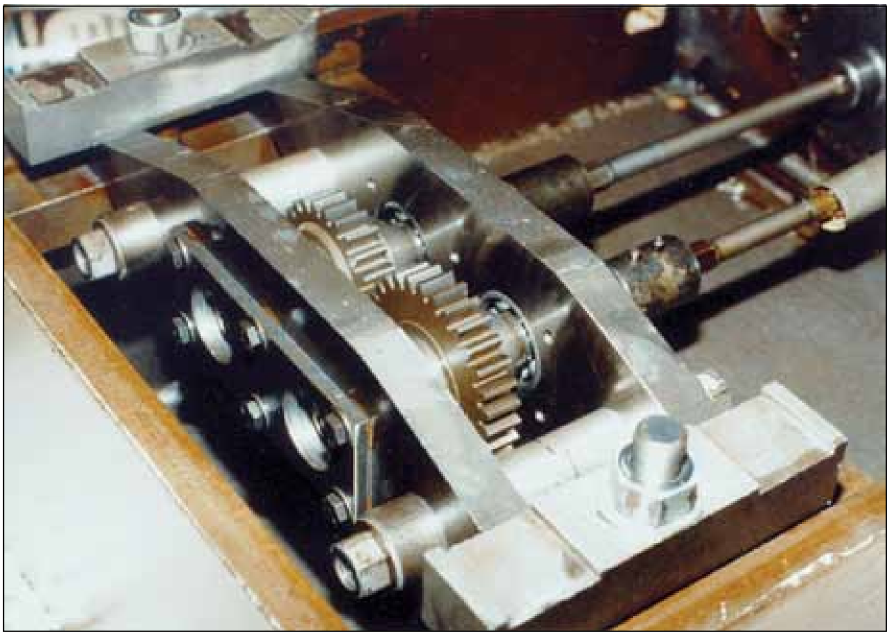
An obvious question that comes to mind asks what types of gears are more susceptible to gear noise. Does it matter? Not really.

"All types of gears are susceptible to gear noise," says Houser, adding, "though gears with very small numbers of teeth, such as single-start worms, have their mesh frequency near the bottom of the audible frequency range and so are less likely to be heard."

Taking a somewhat different view, Lim states, "Lower-quality gears (i.e., those with inaccurate tooth surface profiles) are most susceptible to gear noise. Also, a worn out gear tooth tends to make more noise. Since gear noise is really a system problem, the dynamic interactions between the gear pair and its supporting structures also play a significant role in causing gear noise. Generally speaking, geared rotor systems with stiffer torsional support and those with structural resonances at the mesh frequencies make more noise."

"Spur and straight bevel gears with operating contact ratios under 2.0 generally create more noise than gears with larger contact ratios," Mark says. "Because helical and spiral bevel gears generally have 'total' contact ratios well above 2.0, they generally produce less noise. The noise produced by gears generally decreases as contact ratios (total contact ratio) are increased. The total contact ratio is the sum of the transverse (profile) contact ratio and the axial (face) contact ratio.

Gear measurement is an important step in trouble-shooting the origins of gear noise (courtesy Penn State U).



Test rig with loaded gear set (courtesy Penn State U).

As gear testing in general can be very complex and challenging, creating simulation protocols and models for noise testing is even more so. But without them, researchers would be similar to an explorer without a map or compass.

"Simulation models help us understand the fundamental gear mesh and dynamic behaviors," Lim states. "With that understanding, we can select designs that are less susceptible to gear noise generation and transmission. Also, the simulation models help us to perform many parametric studies that would otherwise not be possible to determine the best possible design solution. The reason is computer simulation is efficient and cheap to do, while experimental study is time-consuming and much more costly.

"There are two types of simulation models used to analyze gear noise. One is a quasi-static tooth contact analysis to simulate the gear tooth engagement problem. This model enables us to study the various tooth design, assembly and mounting conditions that can lead to lower gear mesh excitation. The second is a dynamic analysis of the geared rotor assembly, which can be applied to understand how system dynamics influence gear noise generation and transmission. The model can be applied to both design support structure and gearbox."

"Since I have been involved with developing such simulation models for over 30 years, this is a topic that I could address at great length," Houser says. "Thinking about the simple source-path-receiver network that can be used to describe the process of gear noise generation, we can model each of the stages to help predict gear noise. Our main focus has been on the modeling of gear whine sources—namely, transmission error, gear force shuttling and friction. Here, we need to predict the gear load distribution, which requires the input of the gear micro-geometry (profiles, leads and topographies).

"The abovementioned excitations are a byproduct of the load distribution calculation. Insofar as we understand the manufactured micro-geometry, there is a good correlation between predictions and noise. In one example where manufactured tooth shapes varied from tooth to tooth, we needed to model the tooth topography of each tooth of each gear in order to get a good correlation between prediction and noise. The major finding was that noise tends to decrease with increasing contact ratio, but having the proper micro-geometry of any gear type can minimize noise generation. My colleague, Dr. Raj Singh, has developed similar models for simulating gear rattle."

Is there a permanent fix for gear noise? Not likely, is the consensus.

"Based on today's technological capability and the trajectory of the advancement in gear design, it is not conceivable that gear noise will be completely eliminated," Lim states. "The reason is because we will never be able to cut perfect gears and even if we can, we will never be able to eliminate the effect of system dynamics. We can minimize and control gear noise to the extent that it will not be considered a problem (annoyance).

"Technically, it is always there, but often we can have gear noises that are beneath the background noise levels, hence, not being audible," says Houser. "Using automobiles as an example, if the engine is a noisy diesel engine, background noise is high so gear noise might not be heard, while if I use the same gears in an electrically driven vehicle, noise might be considered excessive."

"Probably no," is Mark's response, adding, "If the modification of the working surfaces is 'perfect' and if the variation in transmitted loading is minimal, there remains the role of friction, which is very hard to entirely eliminate."

So how do researchers and other experts begin to troubleshoot a gear noise issue? Is there an existing set of protocols that provide some degree of direction in order to determine the source? One apparent source, according to our experts, can be found on the manufacturing floor. After all, no one ever said precision gear manufacturing was a walk in the park.

While Mark points out that a source of the above mentioned tooth-meshing harmonics is deviations of the elastically deformed working surfaces from equispaced, perfect involute surfaces of each of the two meshing gears, he goes on to state that "On the other hand, the source of the remaining rotational harmonics, one set from each of the two meshing gears, is tooth-to-tooth geometric variations of the individual working surfaces from each of the two meshing gears, which almost certainly is caused by manufacturing errors. Improvements in manufacturing precision generally will reduce non-tooth-meshing rotational-harmonic amplitudes."

Taking a somewhat less complex approach, Houser believes that "just listening to the nature of the sound may help. If it is a gear whine tone, then one needs to perform a spectrum analysis

continued

to determine the main frequency of the tonal sounds. Usually they will be at mesh frequency and its harmonics, but occasionally there may be a 'ghost noise' that is the result of manufacturing undulations created in the manufacturing process."

"The approach I like to use is to first measure the gear noise 'signature,' " Lim states. "Using that data, I can listen to the sound and perform digital signal processing to better isolate the frequency and sometimes time characteristics. Once that is known, I like to examine the gearbox design to determine the source of excitation. If necessary, I will also want to perform a series of dynamic testing including modal analysis and operating measurements to understand the transmission paths for the gear vibratory energy. Understanding the source of excitation and also the primary transmission paths will go a long way to help mitigate the gear noise problem."

Given the responses from our three experts, one would think it quite possible to begin reducing gear noise at square-one—i.e., the design and manufacture phases. But no, that's not the case. There are a number of reasons for that, and when taken together, the result is that the gear noise issue is kicked to the curb. For manufacturers who ignore gear noise, it adds up to a pay me now or pay me later deal with the devil. But why is that?

"This is often a side or afterthought issue, since they are in a hurry to complete the design and get the product to market," Houser says. "They do not realize that designing a gearbox without consideration given to noise can lead to a substantially more expensive solution.

"It is my belief that most gear manufacturers and users do not understand the nature of gear noise generation and transmission, and also do not have the tools and capabilities to tackle gear noise up front during the design process," Lim says.

And Houser adds to that with "We have been preaching for years that noise should be considered at the design stage, and I think many do use rules of thumb such as increasing contact ratio in their designs. (But) many designers simply use gear rating-type formulas for creating their designs and these calculations give little insight into whether gears will be noisy or not, leaving designers in a situation where they will learn later whether noise is an issue."

University of Cincinnati Professor Teik C. Lim, ASME Fellow, Chang Jiang Chair Professorship award recipient and expert in dynamic analysis and development of precision gears, bearings and drivetrains (courtesy U of Cinn.).

Thus far, we've learned from Messrs. Houser, Mark and Lim that gear noise is a systemic, whole-component design issue, not confined to strictly gear design. Put another way, "System dynamics play a significant role in the dynamic mesh force generation," Lim states. "Also, the system dynamics control the transmissions of gear noise from the gear pair to the exterior surface; one can have a high-quality gear and still have gear noise if the contribution from system dynamics is substantial."

Which brings us back to the need for dependable modeling when striving to eliminate as much potential gear noise as possible from the outset.

"Things like gear system torsional resonances and housing dynamics may also have an effect on gear noise levels," Lim says. "In order to address these concerns it is necessary to perform much more in-depth dynamic modeling. I should also point out that gear rattle analysis requires a detailed model that must include both backlash non-linearities and the dynamics of the driver and driven inertias, thus requiring system knowledge that might not be available to the typical gear designer."

Breaking it down a bit further into Xs and Os, Mark points out that "In a general dynamic system there is coupling or interaction between all parts of the system. Two gears on the same shaft will illustrate this fact. If the shaft is soft (very elastic), the vibration excitation by one gear on the shaft is likely to have only a small effect on the vibration of the other gear on the shaft. However, if the shaft is rigid, the vibration excitation by one gear on the shaft will have a very strong effect on the vibration of the other gear on the shaft. To understand such coupled effects, one needs to treat (by mathematical modeling, simulation or testing) the entire system as one coupled system. Resonance effects can be important."

So if, let's say, "bad design" is the "hammer" and a "gear set" is the "head" that "design" keeps whacking, why not stop doing that? Why the apparently pervasive occurrence of such off-kilter design? The answer, is more complex than the question.

"First of all, gear designs are often done for a specific operating condition and load," Lim explains. "However, they are used under many varieties of operating and loading conditions; an acceptable design for one condition does not automatically mean it is good

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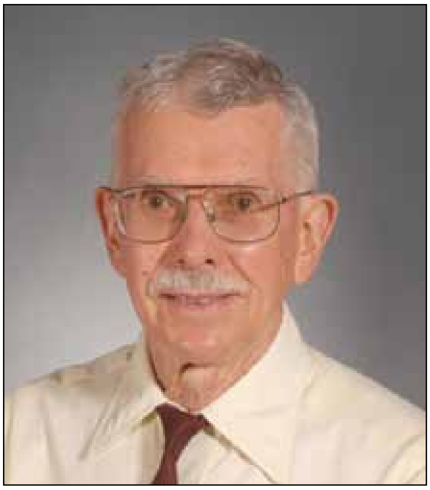

Dr. Bill Mark, senior scientist at the Drivetrain Technology Center/Applied Research Laboratory and professor emeritus of acoustics at Pennsylvania State University (courtesy Penn State U).

for other conditions. Second, gear designs are often done without regard to system dynamics. Since high-quality gears can produce noise when applied inappropriately, it is easy to see why we can encounter gear noise in operation."

Somewhat in the same vein, Mark states, "I suspect the very large benefits of increasing contact ratios are not fully understood by many gear designers. Moreover, gear noise is very sensitive to working-surface modifications. The form and ideal modification are very sensitive to the mean design loading and the range of loadings over which the gears are anticipated to operate. Exceedingly small changes—e.g., in working-surface modifications—can have a large effect on gear noise generation."

And from Houser's perspective, "Every gear application has its own peculiarities, so this is a tough question to answer in a simple manner. From a gear whine perspective, most designers apply micro-geometry corrections that might help at the design load, but hinder the design at lighter loads where noise may be of concern. Without a simulation tool that predicts load distribution, it is extremely difficult to come up with the proper micro-geometry on the gear tooth. The other aspect of this is that once the proper micro-geometry is placed on the gear print, it must be accurately manufactured and this is not always the situation."

And what about material? Do some metals process better than others when assessing gear noise? Not significantly, apparently.

"I do not think material is a big issue," Houser states. "There has long been the adage that plastic gears are quieter than steel, yet, in my dealings with plastic gear users it would seem that a major difficulty with plastic gears is making them quiet. Every now and then we hear that cast iron is quieter than steel, yet they have similar moduli and tooth deflections so their transmission errors would be very similar, hence having the same noise excitation. The only spot where I think material damping has an effect is when there are impacts such as rattle that excite gear blank vibrations that are reduced with damping. But this is likely to be a secondary effect."

Adds Lim, "The materials affect damping and structural dynamics, and that is how it can have an impact on gear noise. Lower damping and sensitive structural dynamics (i.e., the effect of mass and stiffness parameters) can lead to higher gear noise."

Space allows for one last topic on gear noise—the shuttling force that occurs in helical gears. It's important.

"Shuttling force is the side-to-side

Manual transmission set-up at Ohio State University's gear research facility (courtesy OSU).

oscillation of the tooth mesh force along the profile as the tooth pair undergoes the engagement process," Lim explains. "This oscillating force can cause dynamic excitation to the gearbox system. Since it occurs also at the mesh frequency, it contributes to the gear noise response."

Adds Mark, "Because of the helix angle of helical gear teeth, there is an axial component of the force transmitted by the teeth. In the case of a single-helical gear, there will be a time variation to this axial force caused by different numbers of teeth coming into and out of contact. This time varying axial force causes a time-varying force on the thrust bearings, which is a source of vibration excitation. Increasing axial and transverse contact ratios will reduce this time-varying axial force. In the case of double helical gears, if the teeth are not staggered and are perfect (impossible), this axial force would be eliminated."

And from Houser, "As the diagonal lines of contact of helical gears sweep across the tooth, the centroid of the tooth force distribution shifts slightly with the sweep of the lines. When one applies simple statics to this situation, one finds that this simple shifting of the load by only a few microns can result in significant changes in the force at each bearing. These changes will be at mesh frequency, thus giving them the potential of generating mesh frequency noise. The forces due to shuttling are of the same order of magnitude of transmission error forces and are common in helical gears, but also exist in other gear types such as spiral bevel, hypoid and worm gears."

Got all that? Class dismissed.

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Gear Material Risks and Rewards

TECHNOLOGY INVESTMENTS LEAD TO PRODUCT INNOVATION

Matthew Jaster, Associate Editor

The business of raw materials has been rather turbulent of late, with a hodgepodge of press releases calling for equal amounts of optimism and pessimism. One minute the market looks flat, the next minute signs point to a quick recovery. Either way, the gear industry wouldn't get very far without the steel, plastic, powder metal, etc. needed to make the various products. Ignoring mass media hysteria, raw materials seem to have the same problems as other industrial markets: prices are high, the environmental impact needs to be addressed and recovery from economic instability has taken a toll. Toss in an earthquake in Japan, erroneous trade regulations and national debt issues and you've got all sorts of melodrama heading into the fall of 2011.

"The continuing increase in raw material costs along with process fluids and gases remain a challenge for our industry," says Richard Slattery, vice president of engineering at Capstan Atlantic, a global manufacturer of sintered metal products. "This is not industry-specific, as all manufacturing sectors have to deal with this."

"Governments and industry will

continued

DuPont supplies Delrin POM material for planetary transmission gears (courtesy of DuPont).

have to explore policy means to ensure secure, predictable and accessible supply of steel raw materials for all steel producers," says Risaburo Nezu, chairman of the Organization for Economic Cooperation and Development (OECD) Steel Committee. "Global risk factors include concerns regarding financial systems of many economies, remaining sovereign risks due to high levels of public debt, sluggish growth in advanced economies and high oil prices linked to geopolitical risks in the Middle East."

And yet there's hope for bigger and better things in the months ahead. DuPont, for example, is adamantly seeking biomass processing and microbial engineering that will create new bio-fuels and bio-based materials. The sintered metal industry is scratching and clawing its way back from an economic recession that eliminated many jobs, but also created a huge increase in customer demand once the smoke cleared. The steel industry in Japan, the world's biggest steel importer, is finally returning to levels seen before the earthquake and tsunami. This is good news considering initial fears that a supply crunch would negatively impact the Japanese economy for years to come.

Various reports—from *Bloomberg News* to *Industry Week*—state that growing demand for raw materials here and abroad will lead to bigger long-term dividends thanks to new technology, environmental policies and product innovation. Here's a sample of the some of the latest news coming from plastic, steel and powder metal companies:

DuPont Focuses on Renewable Raw Materials

DuPont Chair and CEO Ellen Kullman recently told investors at the JPMorgan Diversified Industries Conference to expect attractive long-term growth from DuPont through product and process innovation, selective investment in attractive areas, broad-based growth, especially in developing markets and a relentless focus on productivity.

"We believe DuPont is uniquely positioned to tackle big global challenges that offer the opportunity for significant top-line growth and value creation," said Kullman. "The recent acquisition of Danisco, (a leader in food ingredients, enzymes and bio-based solutions) is a perfect fit with our growth strategy around feeding a growing population, decreasing dependence on fossil fuels and protecting people and the environment."

"We will leverage Danisco's world-leading capabilities in enzymes and fermentation, with DuPont's strengths in biomass processing and microbial engineering. This combination results in a powerful, integrated set of tools to create the next generation of cost-effective biofuels and biobased materials," said Kullman. "Simply put, our vision is to start with renewable raw materials and create differentiated products with excellent environmental profiles and superior economics for our customers."

Kullman indicated that DuPont continues to focus on market-driven

continued

The steel production peak in 2007 was surpassed in 2010 by 15 percent (courtesy of Jaycy Castandeda).

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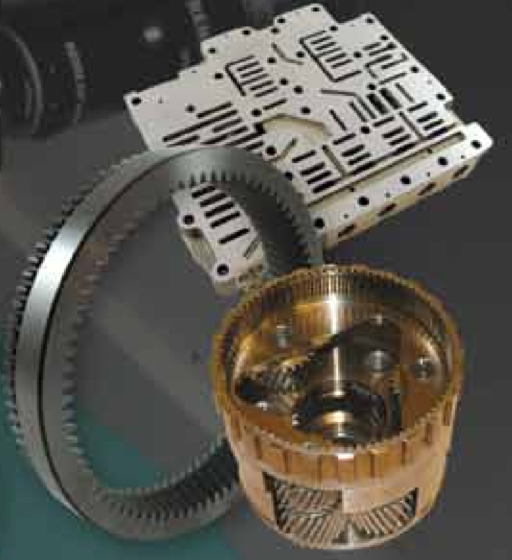

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Ellen Kullman, DuPont Chairman and CEO.

science to meet market needs. In 2010, 31 percent of the company's sales came from products that were introduced within the past four years, "We have made innovation and productivity a part of our DNA at DuPont," Kullman said. "We are currently in the midst of a $1 billion initiative both in fixed cost productivity and working capital productivity. We are well on our way to delivering our 2011 targets of $300 million for each."

"Our businesses are delivering strong results, building on the momentum from 2010 and first quarter 2011," said Kullman. "We expect our resource investments, coupled with innovative product offerings and market demands aligned with the megatrends, will enrich the company's mix of high-growth, high-value offerings. Based on current expectations for long-term sales growth, the high-growth business segments will shift from 48 percent of the portfolio in 2010 to 57 percent by 2015."

In addition, the company recently announced plans to open new global innovation centers, with the first in Asia Pacific. The two innovation centers opening this month include one in Korea, servicing the electronics and automotive industries, and another in Taiwan, focusing on the electronics and communications markets.

Beginning in the fall, new innovation centers in Thailand and India also will be ready to collaborate with customers around renewable energy initiatives and innovations. Additional centers are planned in Latin America, Europe and North America. DuPont's goal is to partner on solutions that fuel local collaboration and application development and engage customers in inclusive innovation—wherever they are in the world.

"The global population has grown to seven billion, generating great need for food, energy and protection. We realize that meeting these needs will require more than science, said Thomas M. Connelly, executive vice president and chief innovation officer. "Globally, we are committed to leading collaborative and inclusive innovations to respond to the challenges facing the world today. Collaboration is the driving force behind establishing these country-focused innovation centers."

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OECD Examines Long-Term Steel Strategies

According to the World Steel Association (WSA), the overall demand of global steel increased by 13.2 percent in 2010 thanks to increased production activity in the industrial sector. The demand in China and other emerging economies has strengthened, surpassing the numbers found before the recent economic crisis. In fact, the production peak in 2007 was surpassed in 2010 by 15 percent. The WSA reports that approximately half of the world's steel output growth occurred in Asia.

The steel market forecast in 2011–2012 is moderately good, according to the WSA. A slowdown in steel production in the second half of 2010 was countered in the first quarter of 2011 where production, led by China, has accelerated 10 percent. Global demand for steel is set to increase this year and next thanks to emerging markets like India and China, according to the OECD Steel Committee.

The OECD believes a discussion is necessary to explore and encourage policies like increasing resource efficiency, promoting recycling and facilitating the use of secondary raw materials. High prices and restrictive trade policy measures are equally a major cause of concern for many involved in the OECD Steel Committee.

Since global production of some raw materials is highly concentrated, there are risks of potential supply disturbances. Additionally, export restrictions and other regulations are increasingly applied in some producer countries, including export bans and licensing requirements, to support downstream production of higher value-added activity such as steel.

Another key issue involves the environmental impact. The iron and steel industry—both major contributors to CO2 emissions—are expected to play a large role in mitigating climate change. This is a double-edged sword as economic development during the 21st century will require ever growing amounts of steel. The Steel Committee reports that governments and industry must prepare for the large, rapid and risky uptake of new technologies when they become commercially available in 10–20 years.

"Policy makers must explore the policies needed to encourage this long-term transition while simultaneously creating a level playing field among producing economies that allows the industry to compete on the basis of fundamental market-driven economic factors," Nezu said in a recent statement on the steel industry. "Global steel trade continued to recover in 2010 with exports worldwide reaching 378 million tons—up by 18 percent compared to 2009. This trend is expected to continue."

Some trade and trade-related measures have nevertheless been applied to steel such as import taxes, import

continued

valuation procedures, differential VAT rebates, and import licensing systems, in addition to the use of trade remedies, according to Nezu.

"While the use of trade remedies has not reached the levels seen in previous market downturns, there are still concerns about unfair trade. However, the product composition of trade appears to be changing, as steel makers in some economies move rapidly up the steel value chain, creating challenges for steel producers in other economies."

The global steel industry has shown resilience to sustain investment in recent years. Sizable investments are made, particularly in emerging economies, not only to modernize existing plants in order to lower energy consumption and produce higher-quality steels, but also to build significant new capacities.

In addition, there are heavy investments to integrate backwards particularly into iron ore, to benefit from the wide gap between the iron ore price and the cost of producing this key raw material.

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Powder Metal Gears Poised for Significant Growth

With approximately 60 percent of its business in the auto industry—75 percent industry-wide—Capstan Atlantic has seen a significant increase in PM consumption over the last 12 months. "Capstan is now enjoying record sales levels, in part due to an uptick in automotive volume," Slattery says. "Focus growth areas are: suspension, powertrain, steering column and EPS (electronic power steering) assist. Powder metallurgy, with its continued focus on high dense, high performance material/process systems coupled with improved dimensional precision, is poised for significant growth within the gear industry."

As mentioned earlier, Capstan Atlantic and the PM industry as a whole took an enormous hit during the economic recession. "The challenge was in re-staffing when business came back," Slattery says. "It ramped up so quickly, we struggled to get trained manpower in place to meet what in some cases was a 400 percent increase in customer demands."

Thankfully, the company-wide strategies put in place during the downturn helped in preparing for the business

Capstan Atlantic is adapting its net shape gear tooth precision technologies to new non-gear applications (courtesy of Capstan).

Capstan has enjoyed new business opportunities with its high-dense crowned gear technology (courtesy of Capstan).

boom that soon followed. "We became a leaner organization as a result of the economic downturn, and are a much healthier company today because of it," Slattery says. "We continue to develop and train our talent internally. We find that if we can find people with a good attitude that are willing and capable of learning, we can train them to be talented PM professionals. Robust training systems are keys to survival when dealing with employee turnover due to retirement, etc."

The biggest challenge facing powder metal manufacturers is the same issue found in both steel and plastic. Customers are having a difficult time accepting price increases. "Discussions surrounding price increases can sometimes put strain on a relationship with a customer. In the end, the objective is to develop a solution that everyone can live with," Slattery says.

On the product side, Capstan Atlantic continues to enjoy new business opportunities with the marketing and sale of its high-dense crowned gear technology. Crowned gears significantly improve load distribution on gear teeth by eliminating the potential of "point loading," while also providing noise reduction.

Gear crowning is a secondary operation performed on an as-sintered preform, and something not previously available to the marketplace in a PM gear. Field tests on single pressed, high dense, crowned, carburized gears have shown a 100 percent increase in contact fatigue endurance, over conventionally supplied heat treated PM gears. This is due to the influence of the crown on contact stress distribution.

The continuing marketing efforts associated with this technology enable penetration of markets not previously considered for powder metallurgy. Further development continues on stabilizing component distortion through heat treatment to provide more precise gears to the marketplace. Current process capability yields gears at AGMA Q8/9 precision levels.

Capstan Atlantic is also adapting its net shape gear tooth precision technologies to new non-gear applications. "There are many toothed, non-involute gear shapes in the marketplace requiring the same level of precision as the gears we currently manufacture,"

continued

Capstan has developed non-involute profile measurement methods to monitor characteristics.

Slattery adds. Capstan is now pursuing these applications and realizing the benefits of the varied markets.

These tooth shapes can be defined by a series of compound radii at X, Y coordinates—or intersecting lines, angles and radii. Precision control of these tooth profiles is critical for features such as strength and noise reduction. Conventional approaches to these technologies have included post-sinter calibration methods such as sizing or machining. Through precise tool control, along with minimal sectional density variation and cleverly employed sinter distortion control methods, Capstan Atlantic is meeting profile tolerances within 25 microns, net shape.

Additionally Capstan has developed variable non-involute profile measurement methods to develop, control and monitor these characteristics. Further work in this area is focused on cam surface geometries, coupled with single pressed high dense methods, targeting aggressive rolling contact fatigue applications.

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Tribology Aspects in Angular Transmission Systems

Part VIII:

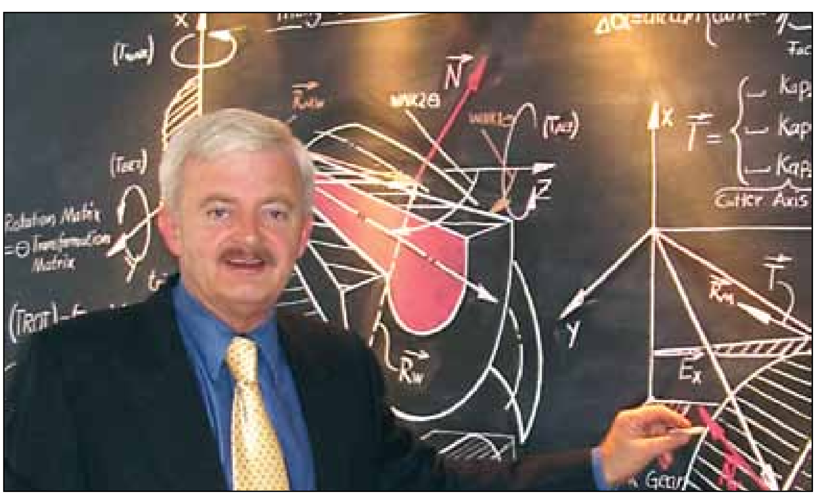
Super-Reduction Hypoid Gears

Dr. Hermann Stadtfeld

(This is the final installment of a Gear Technology*-exclusive eight-part series on the tribology aspects of angular gear drives.* Gear Technology *(Randall Publications LLC) is most grateful to Dr. Stadtfeld and the Gleason Corporation for choosing this magazine as the platform for presenting this very informative and most-relevant series of "teach-ins" to its readers.)*

Design

Super-reduction hypoid gears (SRH) are bevel worm gears with certain differences regarding hypoid gears. If two axes are positioned in space and the task is to transmit motion and torque between them using some kind of gears with a ratio above 5 and even higher than 50, the following cases are commonly known:



Dr. Hermann Stadtfeld *received a bachelor's degree in 1978 and in 1982 a master's degree in mechanical engineering at the Technical University in Aachen, Germany. He then worked as a scientist at the Machine Tool Laboratory of the Technical University of Aachen. In 1987, he received his Ph.D. and accepted the position as head of engineering and R&D of the Bevel Gear Machine Tool Division of Oerlikon Buehrle AG in Zurich, Switzerland. In 1992, Dr. Stadtfeld accepted a position as visiting professor at the Rochester Institute of Technology. From 1994 until 2002, he worked for The Gleason Works in Rochester, New York—first as director of R&D and then as vice president of R&D. After an absence from Gleason between 2002 to 2005, when Dr. Stadtfeld established a gear research company in Germany and taught gear technology as a professor at the University of Ilmenau, he returned to the Gleason Corporation, where he holds today the position of vice president-bevel gear technology and R&D. Dr. Stadtfeld has published more than 200 technical papers and eight books on bevel gear technology. He holds more than 40 international patents on gear design and gear process, as well as tools and machines.*

- Axes cross under an angle (mostly 90°) → Worm Gear Drives (line contact)

- **Axes cross under an angle close to 90° → SRH Gears (line contact)**

To establish line contact in SRH gears, the ring gear is defined by Formate-design geometry and then used as a generating gear for the pinion. In order to define a pinion without mutilations and minimum undercut, the pinion pitch diameter and the normal pitch (equal to normal module times π) are used to calculate the ideal mean lead angle. Figure 1 shows how the SRH pinion with a certain lead angle φ_e is positioned vertically, such that 90° minus the spiral angle β matches the mean lead angle φ_e of the pinion. The last described procedure is done in order to define the hypoid offset. The offset can be changed by increasing or reducing the gear spiral angle. An optical explanation for why bevel worm gears require a different theoretical approach than hypoid gears is illustrated in Figure 2. The normal profile of the hypoid pinion in the top sequence in Figure 2 is easily identified in the top left (front view) or center photos (pinion rotated by the spiral

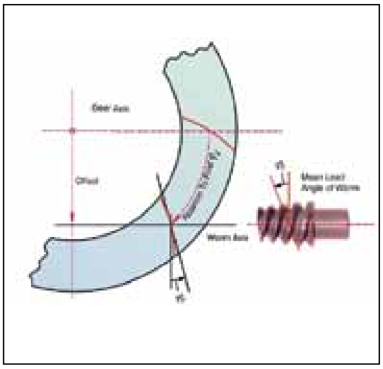


Figure 1—Global SRH design strategy.

Figure 2—Difference between face profile and normal profile.

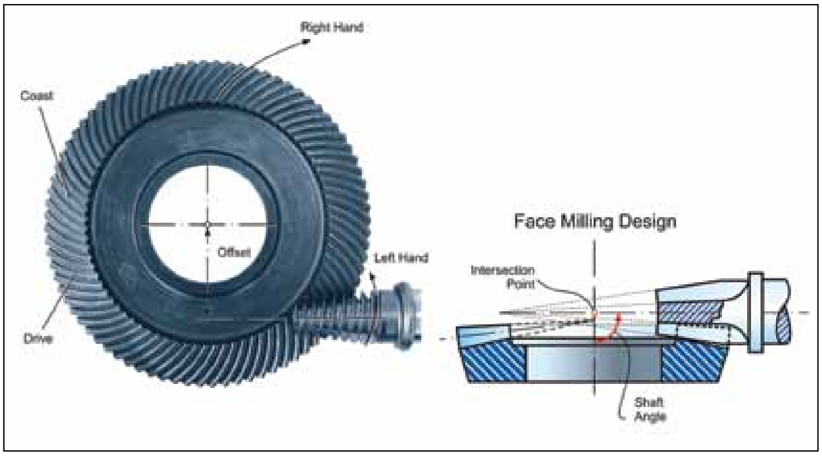


Figure 3—Super-reduction hypoid gear geometry.

angle). And yet the normal profile of an SRH pinion is more easily recognized in the side view (right photos). The reason is that the spiral angle in most cases is larger than 45°, which is why the SRH pinion appears like a tapered ACME screw.

SRH gears have a length sliding between their teeth which is present in any flank surface point and dominates the small amounts of profile sliding. The axes of SRH gears in most cases cross under an angle of 90°. This so-called shaft angle can be larger or smaller than 90°, where shaft angles above 90° can lead to internal ring gears that are often limited in their manufacturability due to cutter interference. However, the axes do not intersect and the smallest distance between them is called the *hypoid offset*. The shaft angle is defined in a plane perpendicular to the offset direction (Fig. 3, right).

SRH gears have a parallel-depth profile along the face width if they are manufactured in the continuous-face hobbing process, or a tapered-depth profile along the face width if the manufacturing is done using the single-indexing face milling process.

SRH gear teeth follow in face width direction a curve on the conical gear and pinion body that lies under an angle to a cone element (spiral angle). The tooth lead function in face width direction, if unrolled into a plane, is an epicycloid or a circle, depending on the manufacturing method. The tooth profile is a spherical involute in a parallel-depth tooth system; it is an octoid in a tapered-depth tooth system. The tooth form with a spherical involute will result in line contact between two mating flanks in each angular position if no crowning has been applied. With an octoid, there will be an initial "natural" profile crowning and, depending on the machining setup, some flank twist. Both effects are utilized together with certain corrective machine settings in order to generate the desired crowning.

The photo of an SRH gear set (Fig. 3) explains the definition of right-hand and left-hand spiral direction and indicates the coast- and drive-side gear flanks. The cross-sectional drawing to the right in Figure 3 illustrates the blank design for parts manufactured in the face milling process (tapered-depth teeth).

Analysis

Since the cited distortions in tapered-depth tooth systems are detected by comparison to conjugate mating flanks, it is possible to define potential contact lines that would apply should the distortions be removed or if load-affected deflections allow for a contact spread. In order to allow for deflections of tooth surfaces, shafts, bearings and gearbox housing—without unwanted edge contact—a crowning in face width and profile direction is applied. A theoretical tooth contact analysis (TCA) previous to gear manufacturing can be performed to observe the effect of the crowning in connection with the basic characteristic of the particular gear set. This also affords the possibility of returning to the basic dimensions in order to optimize them if the analysis results show any deficiencies. Figure 4 shows the result of a TCA of a typical SRH gear set.

The two columns in Figure 4 represent the analysis results of the two mating flank combinations (*see also Part I, "General Explanation of Theoretical Bevel Gear Analysis"*). Using the drive side as the main load transmission direction for SRH gears is a rather binding rule. When the concave gear flanks and the convex pinion flanks are chosen as driving side, then, per definition, this is a "driving-coast side." A driving-coast side is particularly critical in SRH gearing. In spite of spiral bevel

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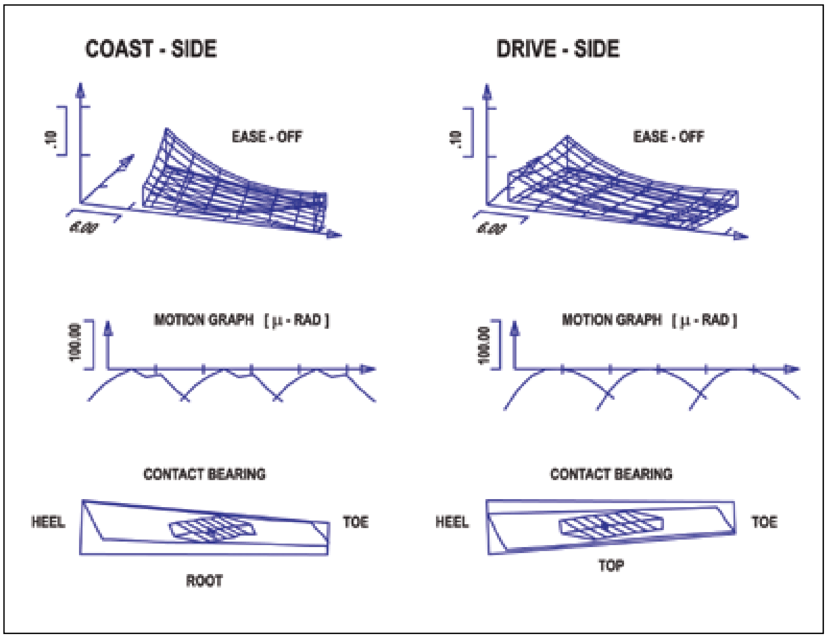

Figure 4—Tooth contact analysis of an SRH gear set.

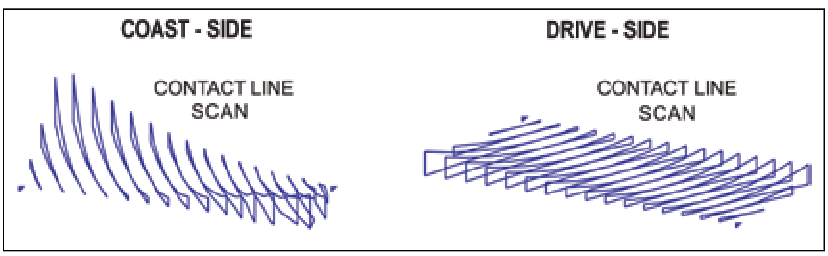

Figure 5—Contact-line scan of an SRH gear set.

and hypoid gears, the axial forces caused by the large-pinion spiral angle dominate and often lead to twice the bending stress in the pinion core diameter at the heel. The fracture risk of SRH gear sets is therefore judged on the tension stress in the pinion core diameter and not on the root of the gear and pinion teeth.

The top graphics show the ease-off topographies. The surface above the presentation grid shows the consolidation of the pinion and gear crowning. The ease-offs in Figure 4 have a combination of length crowning, profile crowning and flank twist, and so a clearance along the boundary of the teeth is established.

Below each ease-off, the motion transmission graphs of the particular mating flank pair are shown. The motion transmission graphs show the angular variation of the driven gear in the case of a pinion that rotates with a constant angular velocity. The graphs are drawn for the rotation and mesh of three consecutive pairs of teeth. While the ease-off requires a sufficient amount of crowning in order to prevent edge contact and allow for load-affected deflections, the crowning in turn causes, in this example, proportional amounts of angular motion variation of about 50 micro radians.

At the bottom of Figure 4, the tooth contact pattern is plotted inside of the gear tooth projection. These contact patterns are calculated for zero-load and a virtual marking compound film of 6 μm thickness. This in essence duplicates the tooth contact, as one may assume, as in rolling the real version of the analyzed gear set under light load on a roll tester while the gear member is coated with a thin marking-compound layer. The contact lines lie under an angle of 55° to the root direction, depending basically on the spiral angle. The path of contact connects the start and stop of meshing; its orientation is mainly in the face width direction.

The crowning reflected in the ease-off results in a located contact zone inside the boundaries of the gear tooth. A smaller tooth contact area generally results from large magnitudes in the ease-off, and the motion graph, and vice versa.

Figure 5 shows 20 discrete potential contact lines with their individual crowning amounts along their length (contact-line scan). The gap geometry in contact-line direction can be influenced by a change in ease-off topography and optimized regarding the gap kinematic cases (*see also Part I, "General Explanation of Theoretical Bevel Gear Analysis," Figure 8*). The gap geometry perpendicular to the contact-line direction (not exactly the same as the path-of-contact direction) does not significantly depend on the ease-off topography; rather, it is mainly dominated by the geometry of the mating tooth profiles. Typical of SRH gears is the lubrication gap change from contact line to contact line. Effects such as those discussed in cases 5 and 6 are likely to be applicable in SRH gears and can also be controlled, to some extent, in SRH ease-off developments.

Figure 6 shows the sliding- and rolling-velocity vectors of a typical hypoid gear set for each path of contact point for the 20 discussed roll positions; each vector is projected to the tangential plane at the point-of-origin of the vector. The velocity vectors are drawn inside the gear tooth projection plane. The points-of-origin of both rolling- and sliding-velocity vectors are grouped along the path-of-contact, which is found as the connection of the minima of the individual lines in the contact-line scan graphic (Fig. 5). The rolling- and sliding-velocity vectors in the present example have the same orientation as the contact lines.

Therefore, in order to investigate the hydrodynamic lubrication properties, employing the information from the contact line scan (curvature and curvature change) and the velocities in Figure 6 will be sufficient (*see also Part I, "General Explanation of Theoretical Bevel Gear Analysis," Figure 8, cases 1–6*).

With the SRH gear set under discussion, the sliding-velocity vectors between toe and heel—right to left—have about the same direction; they consist of a certain profile component and a larger length component. The reasons for this uniform sliding velocity orientation are the high screw motion that is constant along the face width, and the fact that the pitch line is far above the face of the gear tooth (outside of the flank surface).

The rolling-velocity vectors point down and to the right, and all have basically the same orientation. Opposite directions of sliding and rolling velocities (Fig. 6) deliver the lubrication cases 2 or 4 (*see Part I, "General Explanation of Theoretical Bevel Gear Analysis," Figure 8*) that result in an unfavorable negative slippage.

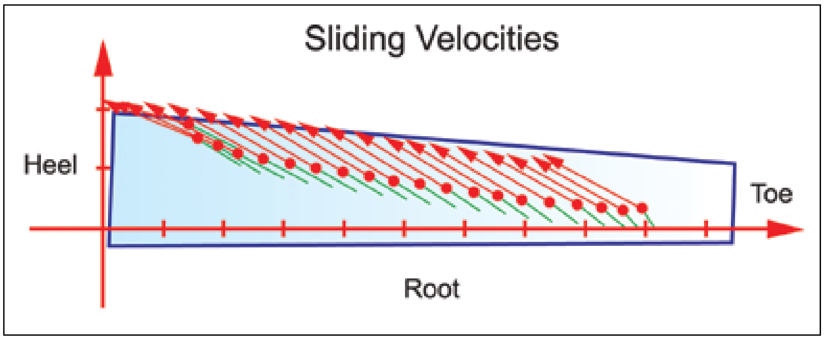

Figure 6—Rolling and sliding velocities of an SRH gear set along the path of contact.

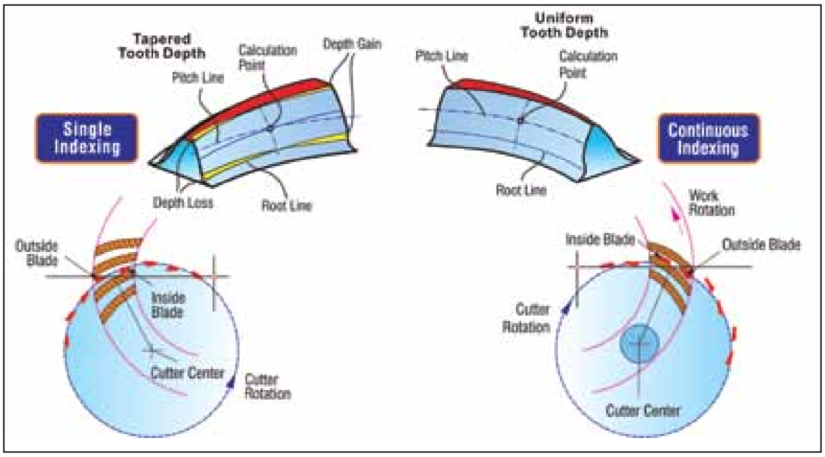

Figure 7—Left: face milling; Right: face hobbing.

Manufacturing

Super-reduction hypoid gears are manufactured in a continuous-indexing face hobbing process or in a single-indexing face milling process. In the face milling process the blades are oriented around a circle and pass through one slot (while they plunge or generate the flanks of that particular slot), as illustrated in Figure 7, left (Ref. 2). The work is not performing any indexing rotation. At the blade tip and in equidistant planes (normal to the cutter head axis) the slot width produced has a constant width between toe and heel. In order to achieve a proportionally changing slot width (and tooth thickness), the root line of face milled bevel gears is inclined versus the pitch line (Fig. 7, left). This modification must be implemented in both members, which is why the face angle requires the same modification as the root angle of the mating member.

In face hobbing (Fig. 7, right)—we observe a group of one inside- and one outside-blade passing through one slot—while the work rotates with:

$\omega_{Work} = \omega_{Cutter} \cdot$ (Number of Cutter Blade Groups)/(Number of Work Teeth)

Due to the relative motion, the following blade group passes through the next slot. The blades in one group are positioned along a spiral, where the sum of the blade groups is oriented around a circle with equal distance to the cutter head center. Due to the described kinematic, the flank lines of the outer and inner flank are epicycloids that divide slot width and tooth thickness in equal fractions of the circumference at any point along the face width. The result is a "natural" slot width taper, proportional to the distance from the pitch apex. A root angle modification is not required or useful because of the already-existing perfect fit of mating teeth and slots.

Hard-finishing after heat treatment of face milled SRH gears is generally done by grinding. Figure 8 provides a view into the work chamber of a free-form bevel and hypoid gear grinding machine during the grinding of an SRH pinion. The grinding wheel grit material is sintered aluminum oxide that is applied with a surface speed of 25 m/sec. The grinding wheel resembles the cutter head geometry, while the grinding machine uses the same set up geometry and kinematic as the cutting machine for the previous soft-machining. Hard-finishing of face hobbed SRH gears is generally done by lapping. Pinion and gear are rolled under light torque while a lapping compound of silicon carbide oil mixture is

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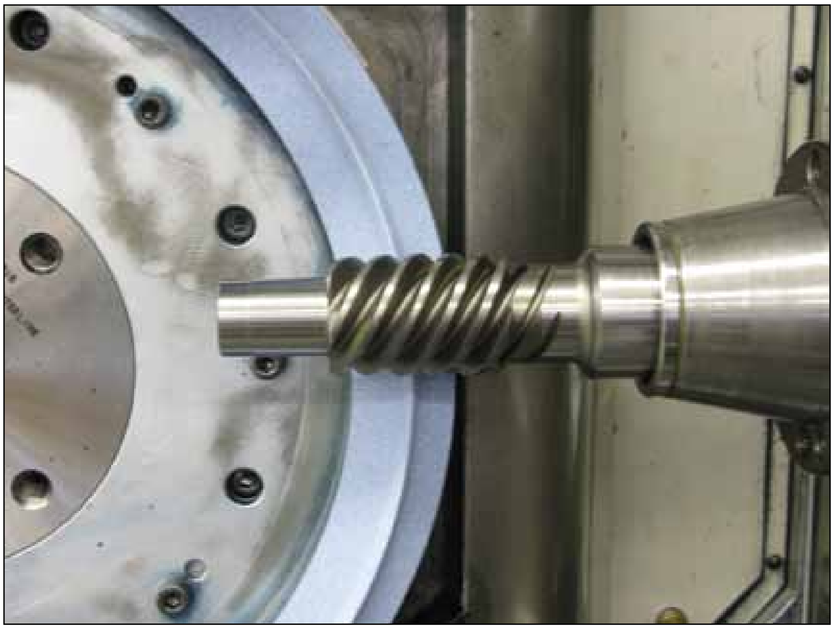

Figure 8—Super-reduction hypoid pinion grinding.

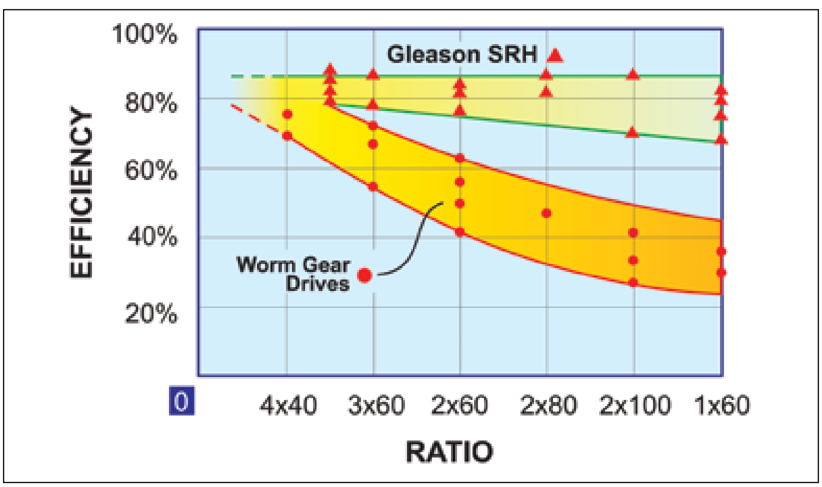

Figure 9—Efficiency comparison.

present between the flanks. Lapping leaves abrasive grain imbedded in the flank surfaces that might lead to several problems such as wear, temperature and lowered efficiency. Lapping of SRH gear sets requires low runout and spacing errors in the parts before the lapping process and very short lapping times. Due to the much higher number of pinion rotations, the lap removal of the pinion surfaces is a multiple of the material removal on the gear flanks. This results in too much lapping on the pinion and almost no lapping on the gear. A compromise is difficult to find; the best recommendation is a very short lapping with low torque (1 Nm to 3 Nm) with the result of a well lapped pinion and a gear which still shows witness marks of the cutting flats.

The efficiency advantage of SRH gear sets over worm gear drives shown in Figure 9 is only achievable in the case of face milled and ground pairs. Grinding assures precise flank surfaces with consistent surface roughness—an important basis for high efficiency. Additionally, the characteristics of the contact-line scan (and the surface curvature perpendicular to the contact lines), in combination with the sliding- and rolling- velocities, are important factors in order to achieve the lowest possible energy dissipation in the tooth mesh.

Application

Most SRH gears are manufactured from carburized steel and are case-hardened to a surface hardness of 60 Rockwell C (HRC) and a core hardness of 36 HRC. Because of the higher pinion revolutions, it is advisable to give the pinion a higher hardness than the ring gear (e.g., pinion 62 HRC, gear 59 HRC). This is more important with increasing ratio and will also reduce the affinity between the pinion and gear flank surfaces and therefore reduce the risk of scoring.

Figure 10 shows the two most common surface damages on SRH flank surfaces due to failure by scoring (left photo) and "frosting" (right photo). Frosting is a surface failure in which a crack propagation 10 to 15 microns occurs beneath the surface (Ref. 3). High surface stress—in combination with a surface roughness characteristic as it is generated by grinding—promotes frosting in the flank areas with negative slippage. Negative slippage is present in SRH gearing within the entire flank surface, which leads to lubrication cases 2 and 4 (*see Part I, "General Explanations on Theoretical Bevel Gear Analysis," Figure* 8). Micro crack propagation is promoted in lubrication case 2 at the left side of the contact point, demonstrating that SRH gear sets are prone to frosting.

In order to achieve surface durability in SRH gear sets, a high surface finish quality and a good lubrication with special high-pressure hypoid oils are recommended in order to maintain a surface-separating oil film. Synthetic hypoid oils provide the best results regarding the prevention of surface damage and the improvement of efficiency. A large contact pattern is also advantageous because of the reduction of the specific surface stress.

The advantages of super-reduction hypoids are:

- **Potentially higher reduction ratio in a one-stage reduction**
- **Back driving requires high torque or is even impossible**

- **Higher efficiency than worm gear drives**
- **Higher efficiency than multiple-stage reduction with standard hypoids**

SRH gears have axial forces that can be calculated by applying a normal force vector at the position of the mean point at each member (*see also Part I, "General Explanation of Theoretical Bevel Gear Analysis*"). The force vector normal to the transmitting flank is separated into its X, Y and Z components, from which the force components in those directions are calculated (Fig. 11).

The relationship in Figure 11 leads to the following formulas, which can be used to calculate bearing-force components in a Cartesian coordinate system and assign them to the bearing-load calculation in a CAD system:

$$F_x = -T / (A_m \cdot \sin\gamma)$$

$$F_y = -T \cdot (\sin\gamma \cdot \sin\beta \cdot \cos\alpha + \cos\gamma \cdot \sin\alpha / (A_m \cdot \sin\gamma \cdot \cos\beta \cdot \cos\alpha)$$

$$F_z = -T \cdot (\cos\gamma \cdot \sin\beta \cdot \cos\alpha - \sin\gamma \cdot \sin\alpha)/ (A_m \cdot \sin\gamma \cdot \cos\beta \cdot \cos\alpha)$$

where:

T	Torque of observed member
A_m	Mean cone distance
γ	Pitch angle
β	Spiral angle (in hypoids for pinion)
α	*Pressure angle*
F_x, F_y, F_z	Bearing load force components

To achieve correct results it is required to use the pinion spiral angle for the SRH pinion and the gear spiral angle for the mating ring gear. Between pinion and gear spiral angle in SRH the following relationship applies:

$$\beta_{pinion} = \beta_{gear} + \arctan(a/A_m);$$

where: a = shaft offset

In Figure 13 the offset *a* is positive for cases 1 and 4 and negative for cases 2 and 3. The pinion spiral angle is positive in all left columns of Figure 13 and negative in the right columns (gear spiral angle has the opposite sign). The bearing-force calculation formulas are based on the assumption that one pair of teeth transmits the torque with one normal force vector in the mean point of the flank pair. The results are good approximations that reflect the real bearing loads for multiple tooth meshing within an acceptable tolerance. A precise calculation is possible with the Gleason bevel and hypoid gear software.

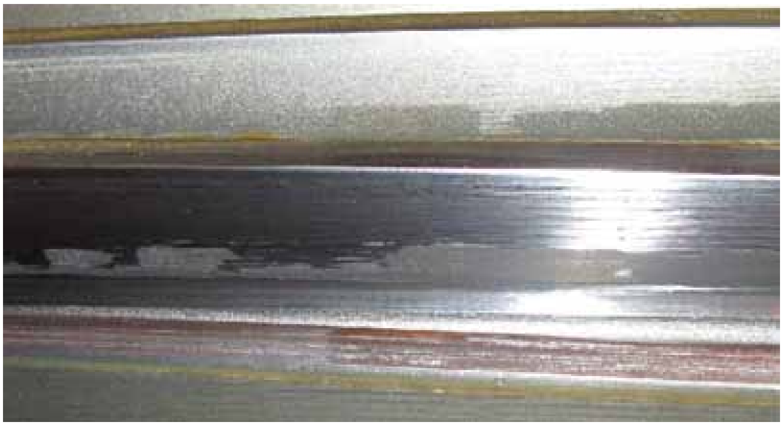

Figure 10—Scoring (left) and frosting (right).

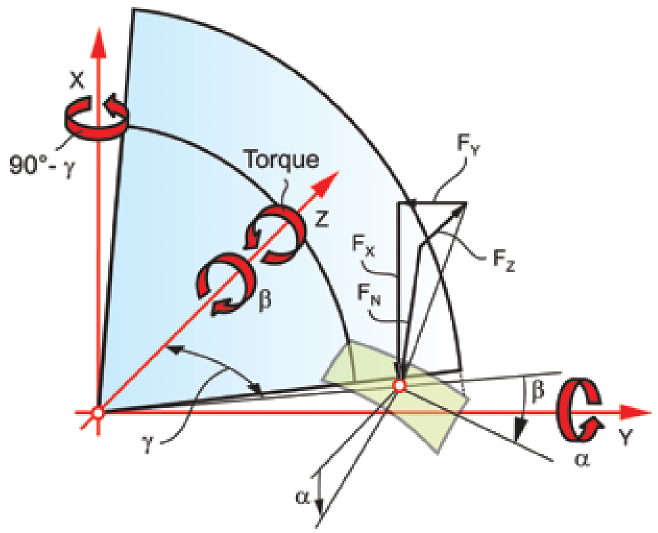

Figure 11—Force diagram for calculation of bearing loads.

Root bending strength is not the criteria for breakage or fracture in SRH gear sets. The weak spot for breakage is the pinion core at the heel. Due to the rather small core diameter—in connection with the notch effect—caused by the high pinion spiral angle, the highest tensile stress concentration is at the end of the teeth (heel) where the square in the drawing of the cantilever beam in Figure 12 is located. The bending moment and the forces are calculated from the force calculation above. Drive operation reduces the tension in the critical fiber of the cantilever beam (Fig. 12) and coast operation increases the tension—which is why in coast direction a significantly lower amount of load than in drive direction can be transmitted in order to assure endurance life.

Hypoid pinions have an advantage if an offset is chosen that increases the pinion spiral angle. Together with the spiral angle, the

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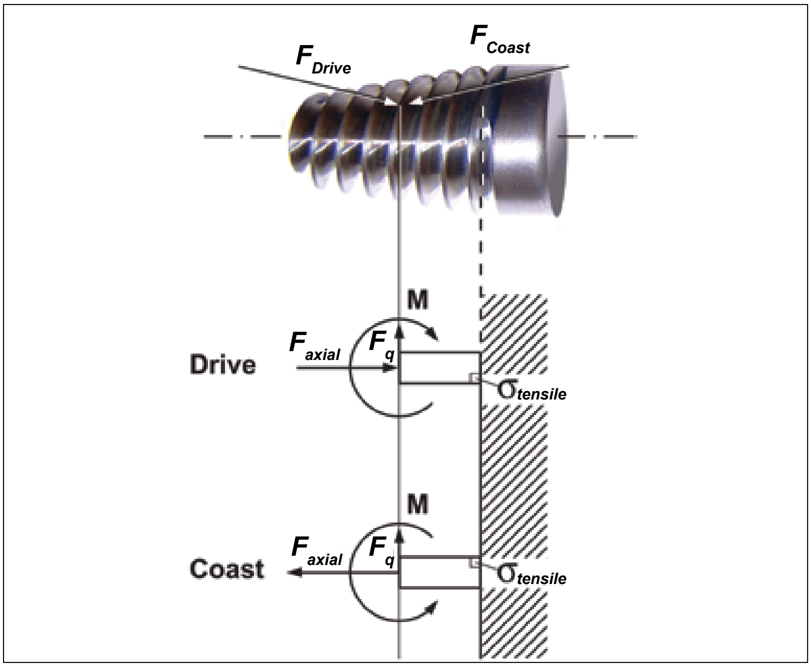

Figure 12—Strength criteria bending stress of pinion core in heel region.

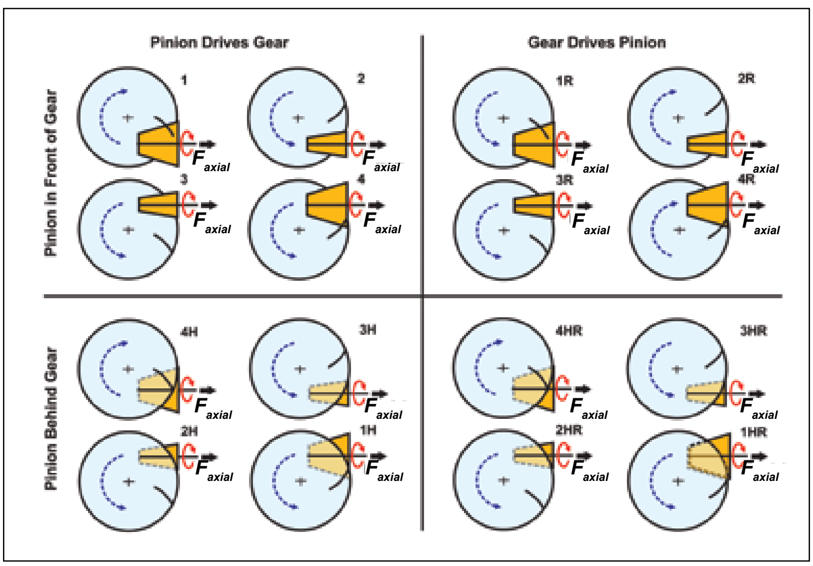

Figure 13—The 16 cases of hypoid offset.

Table 1— Speed limitations for different angular drives

Gear Type	Straight Bevel	Zerol	Spiral Bevel	Face Gears	Beveloid	Hypoid	SRC
Grease	3m/s	5m/s	5m/s	3m/s	5m/s	N/A	N/A
Oil Sump	30m/s	40m/s	60/s	30m/s	70m/s	60m/s	30m/s

pinion diameter increases. Figure 13 has a summary of the 16 different hypoid cases. The left-side column is for a driving pinion, the right-side column for a driving gear. In the upper section the pinion is in front of the ring gear; in the lower section the pinion is behind the ring gear. The torque transmission in all cases utilizes the drive-side. The vector F_{axial} points in the opposite direction in cases of coast-side torque transmission (which will expand the scheme in Figure 13 to 32 cases in total. Cases 1 and 4 (and sub-cases R, H and HR) in Figure 13 are the hypoid cases with a positive offset. The right column in Figure 13 is not practical since back driving is either impossible (self-locking) or results in an extremely low efficiency (e.g., 5% to 10%). Negative offsets (cases 2 and 4 and their sub-cases) are in conflict with the theoretical basics of worm-shaped hypoid pinions and will lead to tooth mutilation. Thus, only cases 1 and 4, along with sub-cases 1H and 4H, are possible configurations for SRH gearing.

SRH gears require—even with low RPMs—a high-pressure oil with additives or special synthetic hypoid oils. A sump lubrication is recommended; the oil level has to cover the face width of the teeth lowest in the sump. Excessive oil causes foaming, cavitations and unnecessary energy loss. The optimal operating direction of SRH gears is the drive-side where the convex gear flank and the concave pinion flank mesh. In the drive-direction (Fig. 11) the forces between the two mating members bend the pinion sideways and axially away from the gear, generating more backlash. Coast-side operation reduces the backlash and also causes higher tensile strength in the pinion core, when compared to a drive operation that can lead to fracture of the pinion core at the heel. Table 1 summarizes the speed limits in connection with various lubricants.

*Note to readers: The release date for the German-language version of Dr. Stadtfeldt's book—*Gleason Kegelradtechnologie*—is September, 2011; published by Expert, Esslingen, Germany; Pages: 500; Price: Euro 51.40; ISBN: 978-3-8169-2983-3. The English-language version—*Gleason Bevel Gear Technology*—will be released approximately one year later, September, 2012.*

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Benefit of Psychoacoustic Analyzing Methods for Gear Noise Investigation

C. Brecher, C. Gorgels, C. Carl and M. Brumm

(This VDI paper was first presented at the 2010 International Conference on Gears, Düsseldorf.)

Management Summary

In recent years gear noise in automobiles has attracted more and more scrutiny. This is due in part to reduced interior noise levels, which make drivetrain noise more noticeable; thus the gear industry's development and quality assurance focus is on the excitation of gear sets. To ensure a constant noise quality objective, characteristics are needed to describe the noise quality of gears and gearboxes. In acoustics it is well known that sound power level and FFT (*Ed.'s note: Fast Fourier Transform—an efficient algorithm to compute the Discrete Fourier Transform—DFT—and its inverse*) analysis are not sufficient to fully describe the sound quality of noise. It is for that reason that with psychoacoustics, additional values have been developed such as tonality, roughness and sharpness to better describe the sensation of human hearing.

Our objective is to provide an overview of the benefits of using psychoacoustic characteristics for describing gear noise. And with that, human hearing and the most important psychoacoustic values will be introduced. Finally, results of noise tests with different gear sets will be presented. The tests are the basis for a correlation analysis between psychoacoustic values and gear characteristics. The conclusion will provide an outlook on further investigations.

Introduction

In the gear development process, noise reduction has always been important. Interior noise is a quality characteristic and influences customer satisfaction (Ref. 1). And while in recent years interior noise has been steadily quieted (Ref. 2; Fig. 1), interior noise reduction in fact further exposes gear noise as one of the dominant noise sources in vehicles.

To attain customer satisfaction, it is not enough to reduce the noise level of the drive train; in future the *sound design* of gearboxes will become necessary. But to date, no characteristics exist with which to evaluate transmission noise.

Within this report psychoacoustic characteristics are used to describe gear noise. A case study was conducted to investigate the correlation between gear noise characteristics and gear geometry.

Psychoacoustics

In gear development and gear production the quality-check of transmissions is based on physical values—unlike the customer who evaluates the sound quality with his hearing. Due to a difference in the performance of human hearing and noise analysis, evaluation of the same noise can differ. Psychoacoustics is one solution for this problem. In psychoacoustics, objective values such as sound level, frequency, bandwidth, duration and degree of modulation are used to calculate psychoacoustic characteristics (Ref. 3). These characteristics have a linear correlation to human noise perception and are based on extensive testing.

The anatomy of human hearing influences noise percep-

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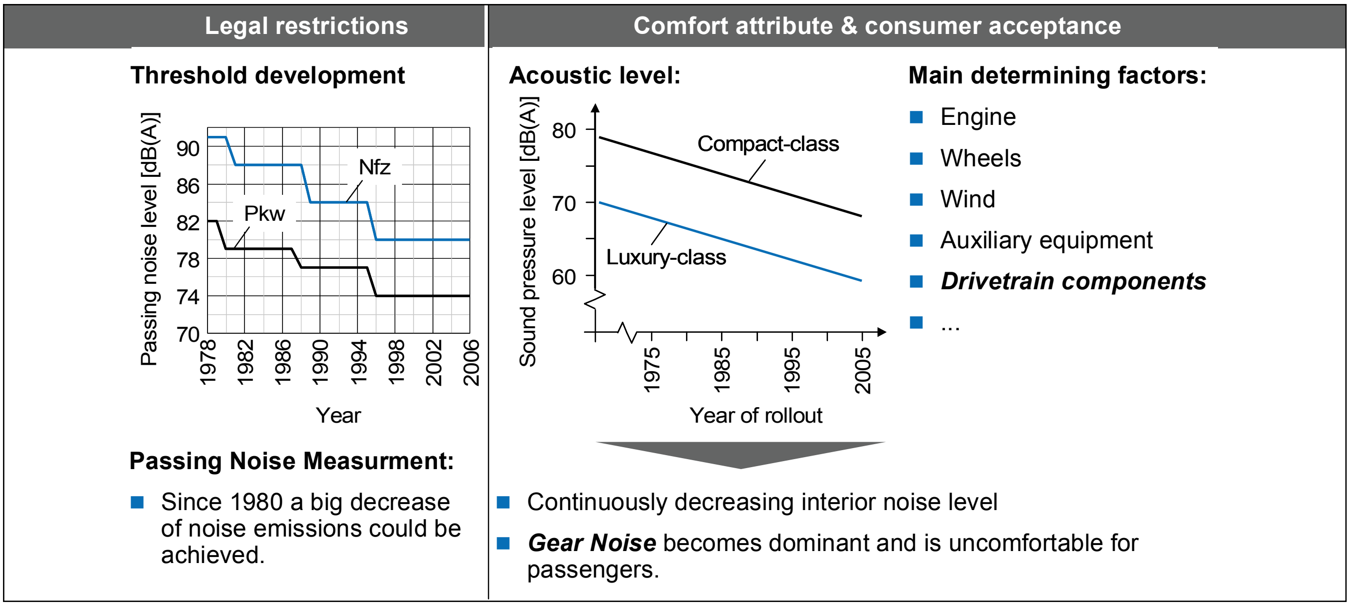


Figure 1—Motivation for psychoacoustics in gear industry (Ref. 2).

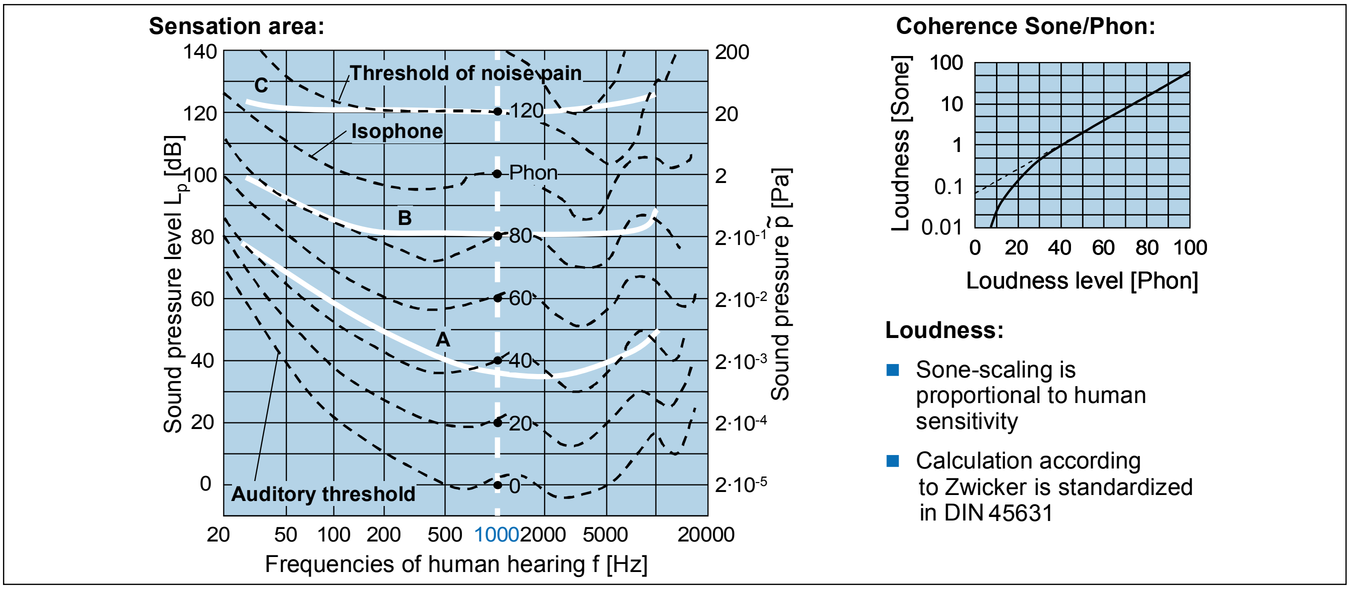


Figure 2—Loudness is a psychoacoustic characteristic.

tion. For example, the length of the outer ear canal leads to an amplification of frequencies between 2 and 4 kHz. Due to Eigen frequencies the transfer function of the inner ear is optimal for frequencies with a range of one-to-two kHz. The sensation area for human hearing is shown in Figure 2; it reaches from 16 Hz to 16 kHz, and the agility of human hearing enables sensate sound pressure from $2 \cdot 10^{-5}$ Pa to 100 Pa. Sound pressure is usually expressed with a leveled scale; the reference value is $2 \cdot 10^{-5}$ Pa. The sensation area displays the isophones (curves of constant loudness) (Ref. 4). The psychoacoustic loudness with its unit sone (a unit of subjective loudness) allows comparison of the loudness level of noise with different frequencies.

Further psychoacoustic characteristics are sharpness, tonality, roughness and fluctuation strength (Fig. 3; Ref. 3). The definition of the scale for the different characteristics takes into account that a doubling of the sensation leads to a doubling of the value.

Design of Experiments

The aim of this report is the investigation of psychoacoustics to evaluate gear noise. Therefore different gear sets with different geometry will be tested in a gear set fixture (Fig. 4; Ref. 5). The fixture is equipped with angle encoders. Additionally, acceleration sensors are mounted close to the bearings and a free-field microphone is located close to the tooth mesh. The fixture enables exchange of the gear set without disassembling the fixture.

To investigate the correlation between gear geometry and gear noise, four different gear sets are tested (Fig. 5). The macro-geometry remains the same for all variants—the pinion has 25 and the gear 36 teeth; the center distance is 112.5 mm and the modulus is 3.5 mm (Ref. 5).

The topology of the first gear set—V1—is conjugated and V1 is the reference for the other variants. V2 has a pitch error that is harmonic to the gear revolution and a wavelength of one-sixth of a gear revolution; V3 has tip relief and crowning;

Tonality

- Value shows whether the sound characteristic is tonal or noisy.
- Tonal sounds occur when the excitation frequency matches the Eigen frequency of the system.
- Unit: 1 tu (tonality unit).

Sharpness

- Sensation that depends on noise contend of high frequencies.
- Unit: 1 acum (Latin: sharp).

Roughness

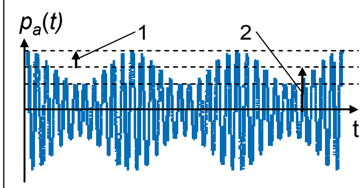
- Envelope fluctuation between 20 and 300 Hz.
- Roughness decreases outside this frequency range.
- Depends on sound pressure level and modulation.
- Unit: 1 asper.

Fluctuation Strength

- Occurs when signal amplitude is changing with very low frequency (4Hz).
- Sounds with a high fluctuation strength call attention.
- Unit: 1 vacil.

Modulation

- No psychoacoustic value.
- Amplitude and frequency modulation are possible.
- Amplitude of carrier wave is oscillating periodically.



$$p_a(t) = \hat{p}_{carrier} \cdot [1 + m \cdot \sin(2\pi f_{mod} \cdot t)] \cdot \sin(2\pi f_{mod} \cdot t)$$

1: Changing component

2: Constant component

Figure 3—Overview of some psychoacoustic characteristics (Ref. 3).

Input

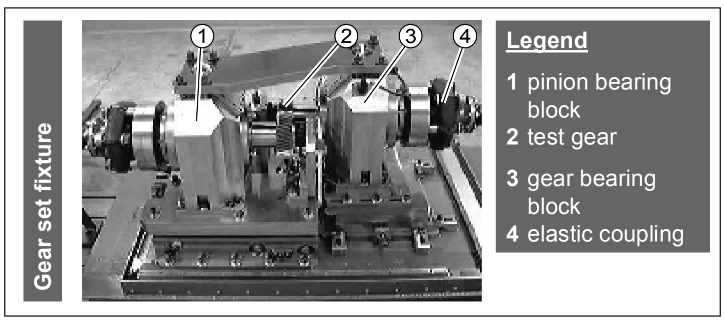
P_{max} = 220 kW
n_{max} = 4,000 rpm
M_{max} = 380 Nm

Output

P_{max} = 155 kW
n_{max} = 2,500 rpm
M_{max} = 1,300 Nm

Measurement devices:

- CM DIGIT NoisyS32
- 4 x acceleration sensor
- 1 x microphone
- 2 x angle encoders



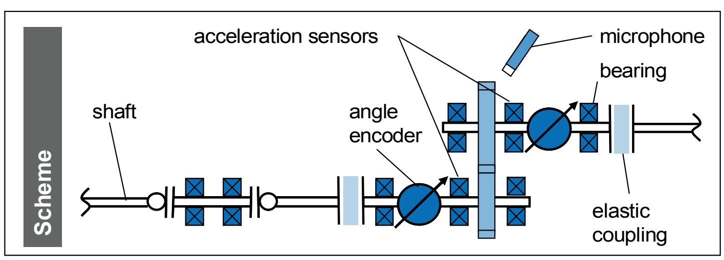


Figure 4—Test set-up.

V4 has only tip relief.

Use of Psychoacoustics for Gear Noise Investigations

What follows is a presentation of the influence of input speed and gear geometry on gear noise. The speed influence was tested by speed sweeps and therefore the input speed was increased from 200 to 3,200 rpm. During one speed ramp, the load was kept constant. Figure 6 shows the influence of the input speed on the gear noise characteristics.

The Campbell graph (Fig. 6) in the upper left corner shows the rising frequencies of tooth mesh harmonics over speed; it also shows the increasing magnitudes of gear noise over speed. The rising sound power level over speed leads to a spike in loudness; the sharpness of the gear noise is also increasing over speed due to the rising mesh harmonics. The lower-right graph (Fig. 6) shows that the tonality of the gear noise is almost independent of speed.

The influence of gear geometry on noise characteristics is seen in Figure 7. Comparison of the noise of the four different gear designs (Fig. 5) is based on the order spectra (sound and vibration) of structure-borne noise and airborne noise. The noise of V1 is characterized by relatively small magnitudes of the mesh harmonics (36th, 72nd). The tip relief of V4 leads to an increase of the magnitudes of the mesh harmonics. The noise signals of V3 show the highest magnitudes of the mesh harmonics. The pitch error of V2 leads to many harmonics of the 6th order referred to gear revolution. This is caused by the wavelength of the pitch error; it has a wavelength of one-sixth of a gear revolution.

The comparison between the order spectra of impact

continued

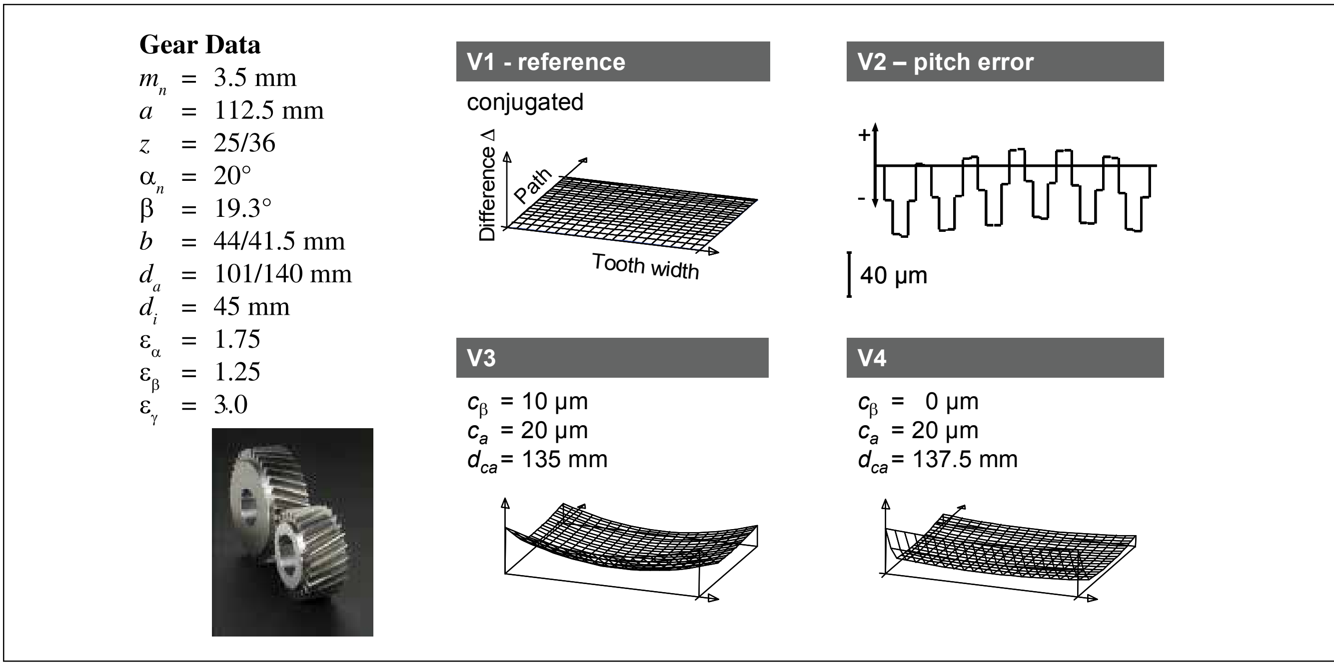


Figure 5—Gear sets.

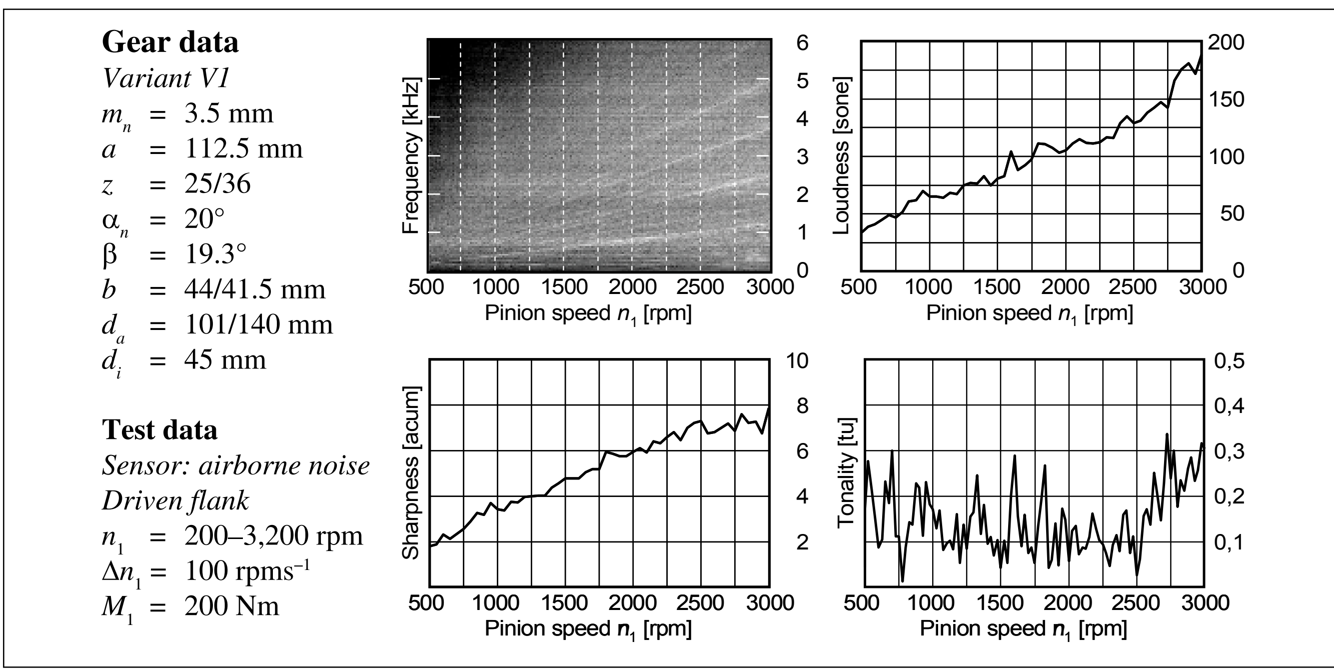


Figure 6—Noise analysis of a speed ramp.

noise and airborne noise shows that the characteristics of both sounds are similar. Dominant frequencies occur in the structure-borne noise signal and in the airborne noise signal—leading to the question of whether psychoacoustic calculations can also be used for structure-borne noise.

Figure 8 shows an overview for the psychoacoustic characteristics of loudness, sharpness and roughness for the airborne noise of the four gear sets. The top-left diagram presents the order cuts of the mesh frequency. The amplitudes of the mesh order differ depending on the variant. The reference gear set (V1) with the conjugated topology has the lowest mesh frequency. V3 radiates noise with the highest content of the tooth mesh order.

Although the tooth mesh amplitude of the noise from V3 is highest, the loudness of the noise from V2 is higher. This is caused by the content of harmonics to the sixth order of the gear revolution in the signal. The excitation caused by the pitch error leads to an increase of the loudness by 50%. Besides V2, the loudness of V3 is also higher than the loudness of the other variants.

The influence of the geometry on sharpness value is very little; the noise of all variants has similar sharpness values and the characteristic roughness is influenced by the pitch deviation.

For the impact-noise sharpness, loudness and roughness are presented in Figure 9. Although the psychoacoustic characteristics are only defined for structure-borne noise, the calculations show a similar trend as do the values for the airborne

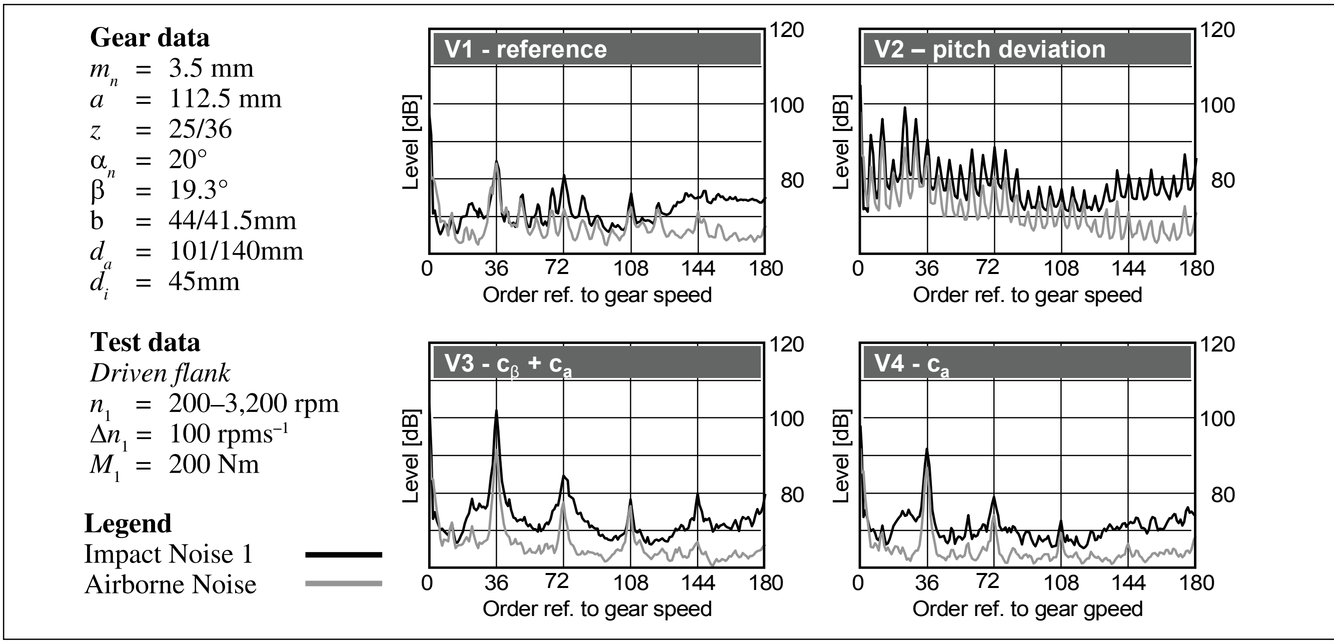


Figure 7—Fourier analysis of impact and airborne noise.

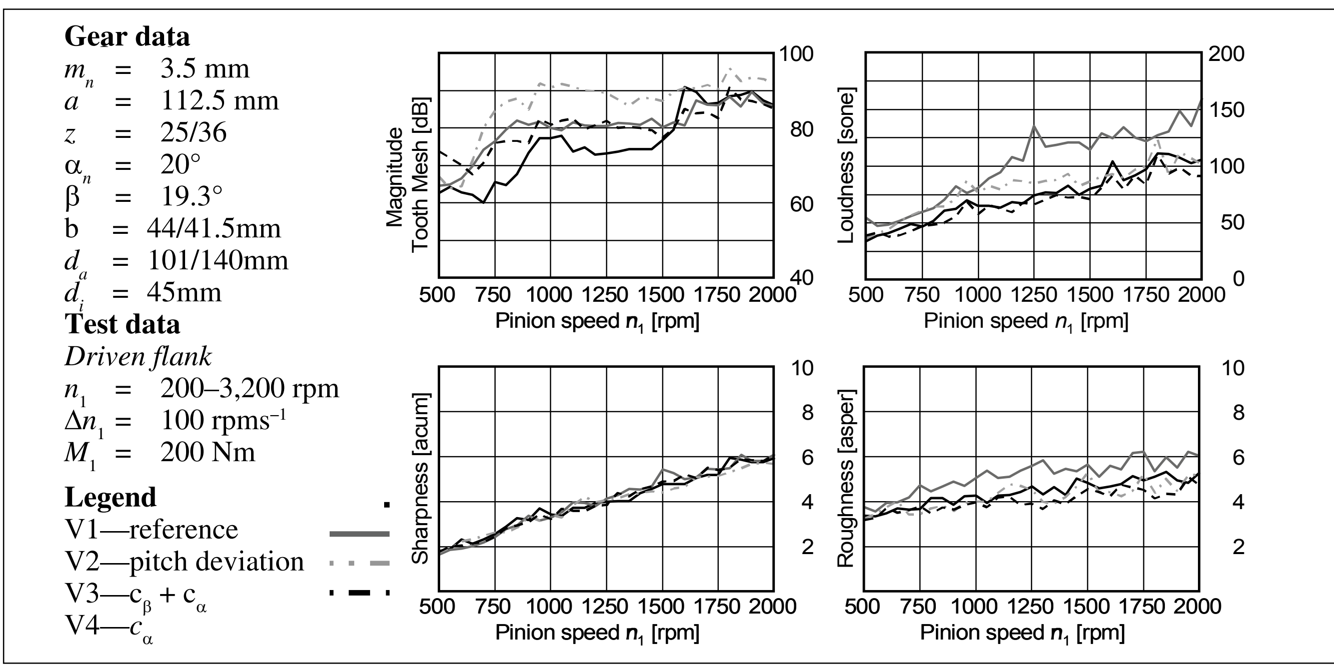


Figure 8—Psychoacoustic evaluation of airborne noise.

noise in Figure 8.

The ranking of the order cut of the mesh frequency of the structure-born noise is the same as the corresponding ranking for the airborne noise. The calculation of the loudness is also influenced by the pitch error. V2 shows the highest loudness level followed by the loudness of V3; the roughness also shows the same ranking for structure-borne noise and airborne noise. By using psychoacoustic calculations for impact noise, the separation effect is even higher than the resolution for airborne noise. One possible reason: the influence of environmental noise in the airborne noise signal. The influence on the structure-borne noise is almost avoided by dampers and elastic couplings.

The example shows that the characteristic of the airborne noise is already included in the impact noise. Due to the transfer path, all frequencies and modulations in the airborne noise are radiated from the surface of the test fixture; thus the oscillation of the surface must already include all the information.

Figure 10 answers the question—Why is V2 noisy and why is its noise so rough?

In comparison to the envelope curve of the reference gear set (V1), the flow of the mesh amplitude of V2 is modulated higher. This signal was recorded at constant speed and constant torque. The signal of the reference gear set is modulated with a dominant frequency of one pinion revolution. The signal of the gear set with the pitch error shows a modulation frequency that meets the sixth order referred to gear speed.

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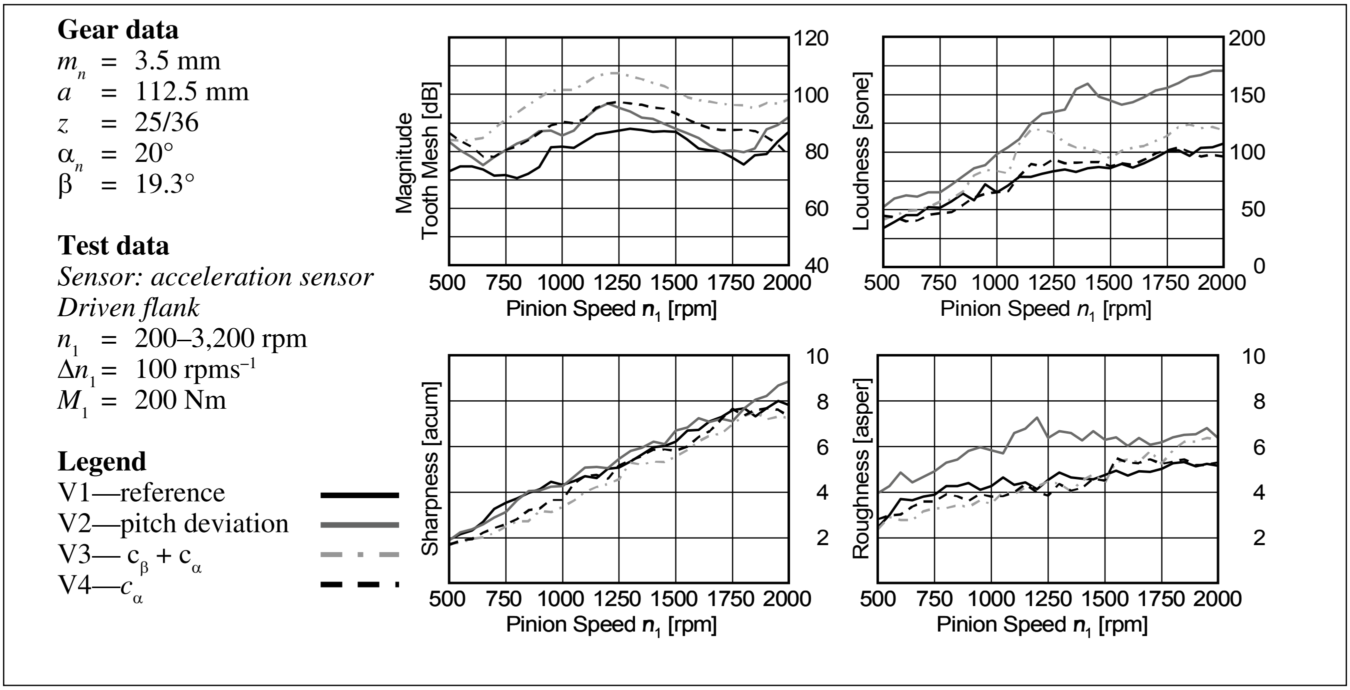

Figure 9—Psychoacoustic evaluation of impact noise.

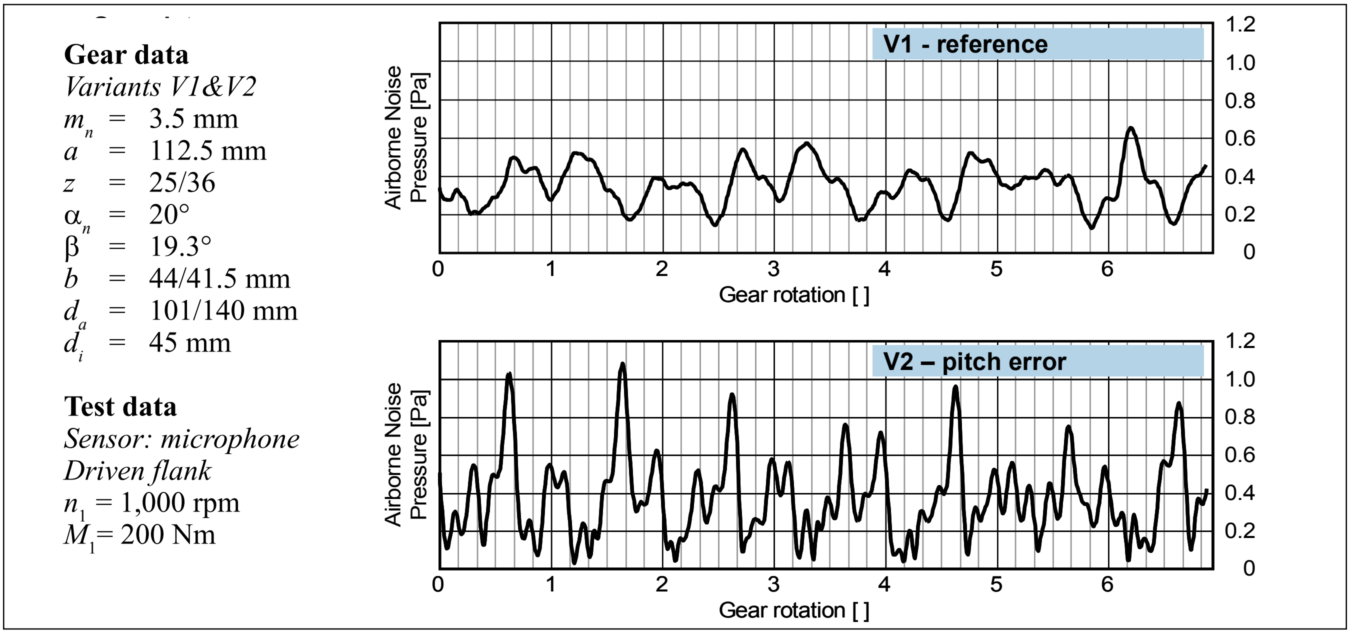

Figure 10—Envelope curve of the mesh frequency.

This strong modulation leads to an increase of the roughness.

The comparison of Figures 8 and 9 shows that all the information included in the airborne noise already exists in the structure-borne noise; the structure-borne noise is exacerbated by oscillating forces in the tooth mesh. For further investigations it is necessary to do a correlation analysis between the transmission error in tooth mesh and the structure-borne noise. The goal of these investigations should be to find possibilities to optimize the noise characteristic by changing the transmission error.

Summary and Outlook

The interior noise level of vehicles continues to decrease; thus noise from gearboxes is not masked by other sounds as in the past and requirements on gear noise quality are rising.

For gear design and quality objectives, physical characteristics are used.

In reality, the consumer rates interior noise subjectively. For that reason evaluation of the same noise can differ.

Psychoacoustics can be one solution. Within this report psychoacoustic characteristics have been introduced and first analyses have been done on gear noise. Therefore different gear sets with a variation of micro-geometry and pitch deviations have been chosen. Noise measurements have been done with these gear sets to investigate the relationship between gearing and gear noise. Sweeps have been done to investigate the speed influence on gear noise. The results show that loudness is not only rising with the rotational speed; noise sharpness is also rising—proportional to the speed.

The result of the comparison of the different gear designs is that the roughness of the gear noise is a characteristic value to determine the pitch deviation of a gear set. It was also possible to transfer the results from airborne noise to structure-borne noise. For the investigated gear sets the psychoacoustic characteristics have been calculated for airborne noise as well as for structure-borne noise. The values show similar results for both signals.

At the end of this report a method was defined to use an input and output synchronous analysis to determine the reason for noise phenomena.

In future investigations:

- The coherence between gearing parameters and noise patterns will be further investigated.
- Different gear designs will be manufactured.
- A variation of micro- and macro-geometry will be done, as well as a variation of run-out and pitch error.
- Psychoacoustic values will be referred to the results of tooth contact analysis to find correlations between psychoacoustic value and tooth contact. Based on this functionality, orientated analyzing methods for gear noise can be developed.

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Manufacturing Method of Large-Sized Spiral Bevel Gears in Cyclo-Palloid System Using Multi-Axis Control and Multi-Tasking Machine Tool

K. Kawasaki, I. Tsuji, Y. Abe and H. Gunbara

Management Summary

The large-sized spiral bevel gears in a Klingelnberg cyclo-palloid system are manufactured using multi-axis control and a multi-tasking machine tool. This manufacturing method has its advantages, such as arbitrary modification of the tooth surface and machining of the part minus the tooth surface. The pitch circular diameter of the gear treated in this study is more than 1,000 mm (approx. 40"). For this study, we first calculated the numerical coordinates on the tooth surfaces of the spiral bevel gears and then modeled the tooth profiles using a 3-D CAD system. We then manufactured the large-sized spiral bevel gears based on a CAM process using multi-axis control and multi-tasking machine tooling. After rough cutting, the workpiece was heat treated and finished by swarf cutting (*Ed.'s note: The removal and cutting of metal in which the axis of the cutting tool is varied with respect to the part being machined*) using a radius end mill. The real tooth surfaces were measured using a coordinate measuring machine and the tooth flank form errors were detected using the measured coordinates. Moreover, the gears were meshed with each other and the tooth contact patterns were investigated. As a result, the validity of this manufacturing method was confirmed.

Introduction

Large-sized spiral bevel gears are often used for power transmission/thermal power generation applications (pulverizing, etc.). Due to the increase of energy demand in the world, the demand for large-sized spiral bevel gears has increased accordingly and may continue so for some time. These gears are usually manufactured based on a cyclo-palloid system, which produces equi-depth teeth, but can also be produced using a face hobbing system, which produces tapered teeth (Refs. 1–3). The spiral bevel gears in this system are usually generated by a continuous-cutting procedure using special gear generating machines. However, the availability of those generators for this use has declined recently, while production costs have not. Therefore, the demand for high-precsion machining of large-sized spiral bevel gears has grown.

This article discusses the manufacture of large-sized spiral bevel gears in the Klingelnberg cyclo-palloid system using multi-axis control and multi-tasking machine tooling. The material of the workpiece was 17CrNiMo06 and was machined using a coated carbide end mill. As a result, the detected tooth flank form errors were small.

Moreover, the tooth contact patterns of the manufactured large-sized spiral bevel gears were observed and those positions were good.

Tooth Surfaces of Spiral Bevel Gears

The generator and cutter heads that Klingelnberg manufactures are typically utilized in spiral bevel gear cutting in the cyclo-palloid system. The equi-depth teeth of the complementary crown gear are produced one after another by the rotating and turning motions of the cutter in this method—i.e., the tooth trace of the complementary crown gear is an extended epicycloid. Therefore, the spiral bevel gears in this system are generated by a continuous cutting procedure.

Figure 1 shows the basic concept that produces an extended epicycloid. O-*xyz* is the coordinate system fixed to the crown gear and the *z* axis is the crown gear axis. O_c is the center of both the rolling circle *R* and the cutter. The cutter fixed to the rolling circle *R* rotates under the situation. OO_c is the machine distance and is denoted by M_d. When the rolling circle *R* of radius *r* (*Md–q*) rolls on the base circle *Q* of radius *q*, the locus on the pitch surface described by the point *P* which is a point fixed to the circle *R* is an extended epicycloid. When the spiral bevel gear is generated for hard cutting on the special generator after heat treatment, a cutter with circular-arc cutting edges is used. These circular-arc cutting edges provide a profile modification to the tooth surfaces of the generated gear. Therefore, a cutter with circular-arc cutting edges is considered in this article.

Figure 2 shows the cutter with circular cutting edges. O_c-$x_c y_c z_c$ is the coordinate system fixed to the cutter. O_c is the cutter center; z_c is the cutter axis; r_c is the cutter radius; γ is the pressure angle of the inner cutting edge of the cutter; ρ is the radius of the curvature of circular arc cutting edge; y_{ci}, z_{ci} are the coordinates of the center of curvature of circular arc in plane x_c = 0, and are expressed as a function of γ and ρ (Ref. 7); θ is the parameter which represents inner curved line. The inner cutting edge X_c is expressed on plane $y_c z_c$ in Oc-$x_c y_c z_c$ by the following equation:

$$\boldsymbol{X}_c(\theta) = \begin{bmatrix} 0 \\ y_{ci} + r_c \cos\theta \\ z_{ci} - r_c \sin\theta \end{bmatrix} \quad (1)$$

The surface of the locus described by X_c in O-*xyz* is expressed as:

$$\boldsymbol{X}(v,\theta) = \boldsymbol{C}(\theta_1)\boldsymbol{X}_c(\theta) + \boldsymbol{D}(v) \quad (2)$$

where *C* is the coordinate transformation matrix for the rotation about *z* axis:

$$\boldsymbol{C}(\theta_1) = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\theta_1(v) = \frac{M_d v}{r} + \Theta_0$$

$$\cos\Theta_0 = \frac{R_m^2 + r_c^2 - M_d^2}{2R_m r_c} \quad (3)$$

$$\boldsymbol{D}(v) = \begin{bmatrix} -M_d \sin(v - \theta_0) \\ M_d \cos(v - \theta_0) \\ 0 \end{bmatrix}$$

$$\cos\theta_0 = \frac{M_d^2 + R_m^2 - r_c^2}{2M_d R_m}$$

In Equations 2 and 3, *v* is a parameter which represents the rotation angle of the cutter about the *z* axis, and R_m is the mean cone distance (Fig. 3). *X* expresses the equation of the tooth (tool) surface of the complementary crown gear. The unit normal of *X* is expressed by *N*.

The complementary crown gear is rotated about the *z* axis by angle ψ and generates the tooth surface of the spiral bevel gear. We call this rotation angle ψ of the crown gear the generating angle. When the generating angle is ψ, *X* and *N* are rewritten as *X*ψ and *N*ψ in O-*XYZ* assuming that the coordinate system O-*xyz* is rotated about the z axis by ψ in the coordinate system O-*XYZ* fixed in space. When ψ is zero, O-*XYZ* coincides with O-*xyz*.

Assuming the relative velocity *W*(*X*ψ) between crown gear and generated gear at the moment when generating angle is ψ, the equation of meshing between the two gears is as follows (Refs. 8–9):

$$\boldsymbol{N}_\psi(v,\theta;\psi) \cdot \boldsymbol{W}(v,\theta;\psi) = 0 \quad (4)$$

From Equation 4 we have θ = θ (*v*, ψ). Substituting θ (*v*, ψ) into *X*ψ and Nψ, any point on the tool surface of the crown gear and its unit normal are

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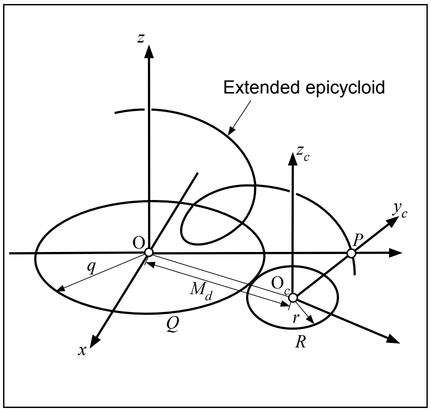

Figure 1—Extended epicycloid.

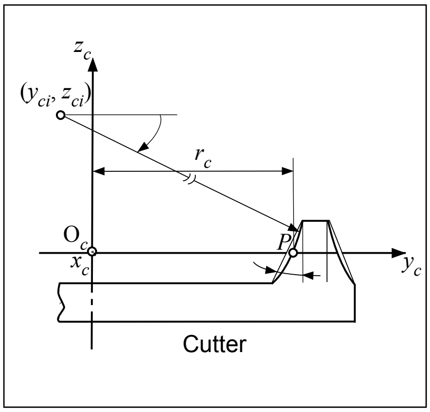

Figure 2—Cutting edges of cutter.

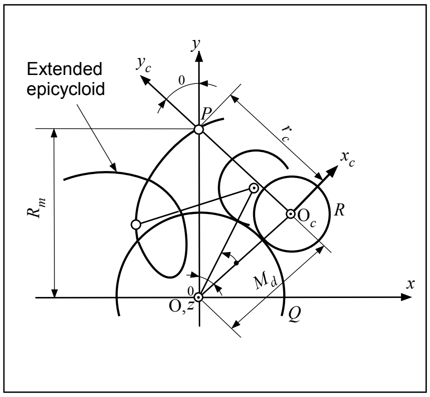

Figure 3—Locus of cutting edge.

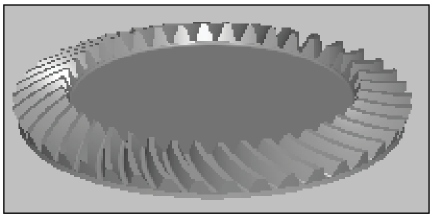

Figure 4—Tooth profile of gear modeled using 3-D CAD system.

Figure 5—Tooth profile of pinion modeled using 3-D CAD system.

Figure 6—Gear workpiece on multi-tasking machine.

defined by a combination of (v, ψ), respectively (*Ed.'s note: Or normal vector—the normal to a surface is a vector perpendicular to it. The normal unit vector is often desired, sometimes known as the "unit normal."*). When the tool surface of the complementary crown gear in O-*XYZ* is transformed into the coordinate system fixed to the generated gear, the *convex* tooth surface is expressed. A similar expression is applied to the *concave* tooth surface. In this case, the difference of the turning radius between inner and outer cutting edges E_{xb} that provides a crowning to the tooth surface of the generated gear should be considered. The convex and concave tooth surfaces of the gear are expressed as X_g and X_g', respectively. The concave and convex tooth surfaces of the pinion are expressed as X_p and X_p' respectively. Moreover, the unit nomals of X_g X_g' X_p and X_p' are expressed as N_g N_g' N_p and N_p'.

CAD/CAM System

The numerical coordinates on the tooth surfaces X_g X_g' X_p and X_p' of the spiral bevel gears were calculated based on the concept in the previous section. Moreover, those unit normals N_g N_g' N_p' and N_p were also calculated. Table 1 shows the dimensions of the spiral bevel gears. Table 2 shows the cutter specifications and machine settings in the calculation of the design; the PCD (pitch circle diameter) of the gear is 1,350 mm (approx. 53").

The determined coordinates are changed by the phase of one pitch after the tooth surfaces X_g X_g', X_p and X_p' are calculated. This process is repeated and produces the numerical coordinates on other convex and concave tooth surfaces. When the range-of-existence of the workpiece that is composed of the root cone, face cone, heel and toe, etc., is indicated, the spiral bevel gear is modeled.

Figures 4 and 5 show the tooth profiles of the gear and pinion modeled using a 3-D CAD system based on the calculated numerical coordinates. The tool pass is calculated automatically after checking tool interferences, choosing a tool and indicating cutting conditions. In this way the CAM process is realized; when the numerical coordinates of the tooth surfaces are calculated, the tooth surfaces are estimated by the smoothing of a sequence of points, removal of the profile of undercutting, offset of tool radius and generation of NURBS (non-uniform rational basis-spline) surface (generated from a series of curves). Moreover, by virtue of calculations of intersecting curved lines of convex and concave tooth surfaces—and sectional curved line—an approximation of straight line is conducted. This approach "escape" is added in order to avoid the interference. When the attitude of the tool and coordinate transformation is conducted, NC data and IGES (initial graphics exchange specification) data for the machining and display are obtained.

Manufacturing of Large-Sized Spiral Bevel Gears

The gears were manufactured based on CAD/CAM system mentioned above. The manufacturing processes were divided into three parts—roughing, semi-finishing and finishing machining.

Manufacturing of gear. The gear was machined by a ball end mill utilizing a vertical, three-axis machining center. However, the gear could

Table 1— Dimensions of spiral bevel gear.

	Pinion	Gear
Number of teeth	16	40
Pitch circle diameter	540.0 mm	1,350.0 mm
Pitch cone angle	21.801 deg.	68.199 deg.
Hand of spiral	Right	Left
Normal module	24.9799	
Shaft angle	90 deg.	
Spiral angle	32 deg.	
Pressure angle	20 deg.	
Mean cone distance R_m	727.0 mm	
Face width	185.0 mm	
Whole depth	56.21 mm	

Table 2 — Cutter specifications and machine settings.

Cutter radius	r_c	450.0 mm
Radius difference	E_{xb}	4.5 mm
Radius of curvature of circular arc	ρ, (ρ')	3,500 mm
Cutter blade module		23.0 mm
Pressure angle		20 deg.
Base circle radius	q	546.9441 mm
Machine distance	M_d	610.4189 mm

not be machined efficiently due to the machining using only one point on the end mill. This manufacturing method was not suitable for the large-sized gear with a PCD of more than 1,000 mm. Moreover, the accuracy of machining was lacking. Therefore, a five-axis control machine (DMG Co., Ltd. DMU210P) was utilized. In this case, the plural surfaces—but not the installation surface—can be machined and a tool approach from an optimal direction can be realized using multi-axis control, as the structure of the two axes of the inclination and rotation, in addition to 3 axes of straight line, are added. It is therefore possible to use a thicker tool. This is expected to reduce the machining time and to obtain better roughness values. Cemented carbide radius end mills for hard cutting were used in the machining of the tooth surface. The number of edges was 12, and the diameters of end mills were 20 mm and 10 mm, respectively. Ball end mills were used in the machining of the tooth bottom. The number of edges was again 12, and the diameters of the end mills were 10 mm and 5 mm, respectively. The gear blank made out of 17CrNiMo06 was prepared. The tool pass was 1 mm for the large-sized gear. First, the gear blank was rough-cut and heat treated. The gear was then semi-finished with the machining allowance of 0.2 mm after heat treatment. Finally, the gear was finished with the machining allowance of 0.05 mm by swarf cutting that is machined using the side of the end mill. Machining utilizing the advantages of multi-axis control and multi-tasking machine tooling in swarf cutting should deliver high accuracy and high efficiency.

Table 3 shows the conditions for semi-finishing and finishing in gear machining. Figure 6 shows the gear workpiece on the multi-axis control and multi-tasking machine; Figure 7 shows the cutting of the gear. The machining time of one side in rough-cutting is about six hours; and with semi-finishing and finishing, about seven hours. The machining was completed with no complications.

Manufacturing of pinion. A five-axis control machine (Mori Seiki Co., Ltd. NT6600) was utilized for pinion machining. The radius end mills made of cemented carbide for a hard cutting tool were used in machining the tooth surface. The number of edges was 12, and the diameters of end mills were 20 mm and 16 mm, respectively. Ball end mills were used in the machining of the tooth bottom. The number of edges was 12 and the diameters of end mills were 10 mm and 5 mm, respectively. The material of the pinion was the same as that of the gear. The pinion blank was rough-cut and heat treated. The pinion was then semi-finished with the machining allowance of 0.2 mm after heat treatment. Moreover, the pinion was finished with the machining allowance of 0.05 mm by swarf cutting. Table 4 shows the conditions for semi-finishing and finishing in pinion machining. Figure 8 shows the pinion on the multi-axis control and multi-tasking machine. The machining time of one side in rough cutting was about eight hours, and with semi-finishing and finishing, about 32 hours. The machining was again finished without trouble.

Tooth flank form error and tooth contact pattern. The real gear and pinion tooth surfaces were measured using a coordinate measuring machine and compared with nominal data using the coordinates and the unit surface normals (Refs. 10–13). A Sigma M&M 3000 developed by Gleason Works was utilized. This measuring machine corresponds to large-sized spiral bevel gears. Figure 9 shows the measured result of the gear and Figure 10 shows that of the pinion. The tooth flank form errors are no more than about ± 0.06 mm and pitch accuracy is Class-1 JIS (Japanese Industrial Standards) for both the cases of the gear and pinion. We de not believe that these errors will have an influence on the tooth contact patterns for large-sized spiral bevel gears.

The gears were set on a gear meshing tester and the experimental tooth

continued

Figure 7—Swarf cutting of gear.

Figure 8—Pinion workpiece on multi-tasking machine.

Table 3 — Conditions of gear machining.

Processes	Diameter of end mill (mm)	Revolution of main spindle (rpm)	Feed (mm/min.)	Depth of cut (mm)	Time/one side (min.)
Semi-finishing	20.0	2,000	1,150	0.3	110
Finishing	20.0	2,200	1,100	0.05	310

Table 4 — Conditions of pinion machining.

Processes	Diameter of end mill (mm)	Revolution of main spindle (rpm)	Feed (mm/min.)	Depth of cut (mm)	Time/one side (min.)
Semi-finishing	16.0	2,800	1,100	0.2	480
Finishing	16.0	3,300	1,100	0.05	1,440

contact patterns were investigated. Figures 11 and 12 show the results of the tooth contact patterns on the gear tooth surfaces of the drive and coast sides, respectively. The tooth contact pattern is positioned at the center of the tooth surface and its length is about 50% of the tooth length, based on the analysis of the tooth contact pattern. The experimental tooth contact patterns are positioned around the center of the tooth surfaces of both drive and coast sides, respectively, although the length of the tooth contact pattern on the drive side is somewhat smaller. From these results the validity of the manufacturing method using multi-axis control and multi-tasking machine tooling was confirmed.

Summary/Conclusions

Large-sized spiral bevel gears are usually manufactured based on a cyclo-palloid system by a continuous cutting procedure using a special generator.

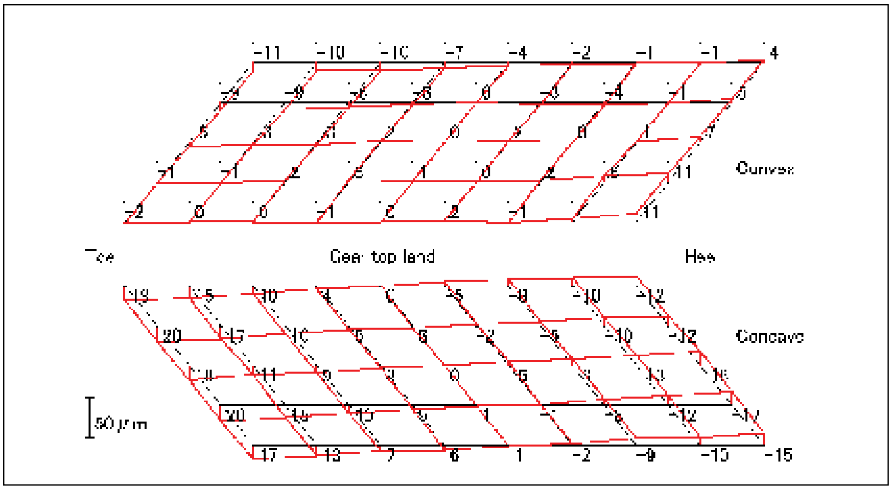

Figure 9—Measured result of gear (μm).

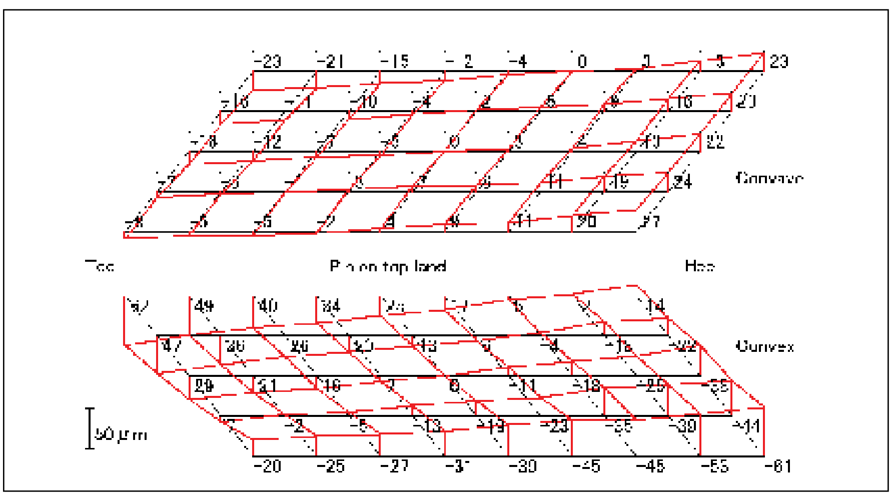

Figure 10—Measured result of pinion (μm).

Figure 11—Tooth contact pattern of drive side.

Figure 12—Tooth contact pattern of coast side.

However, production of the machine tools corresponding to the large-sized spiral bevel gears has recently decreased and the machines themselves are expensive.

In this paper, a manufacturing method of large-sized spiral bevel gears in the Klingelnberg cyclo-palloid system using multi-axis control and multi-tasking machine tooling was proposed. For this study, first the numerical coordinates on the tooth surfaces of the spiral bevel gears were calculated and the tooth profiles were modeled using a 3-D CAD system. The large gears were manufactured based on a CAM process using multi-axis control and multi-tasking machine tooling. After rough cutting, the workpiece was heat treated and finished by swarf cutting using radius end mills. The real tooth surfaces were measured using a coordinate measuring machine and the tooth flank form errors were detected using the measured coordinates. Moreover, the gears meshed well and the tooth contact patterns were investigated. As a result, the validity of this manufacturing method was confirmed.

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State-of-the-Art Broaching

William R. Stott, Managing Editor

To say that broaching is a mature industry is an understatement. It's often perceived as being old, dirty technology that's not very high-tech. It's the way our grandfathers used to crank out parts by the millions for automotive and other high-volume applications. To some extent, that perception is true. Broaching's sweet-spot is still its ability to manufacture large numbers of the same part at an extremely low cost-per-piece.

But there are a number of companies working to change the way broaching is perceived, and over the past 10 years, they've incorporated significant technological changes to make the process more flexible, productive and accurate.

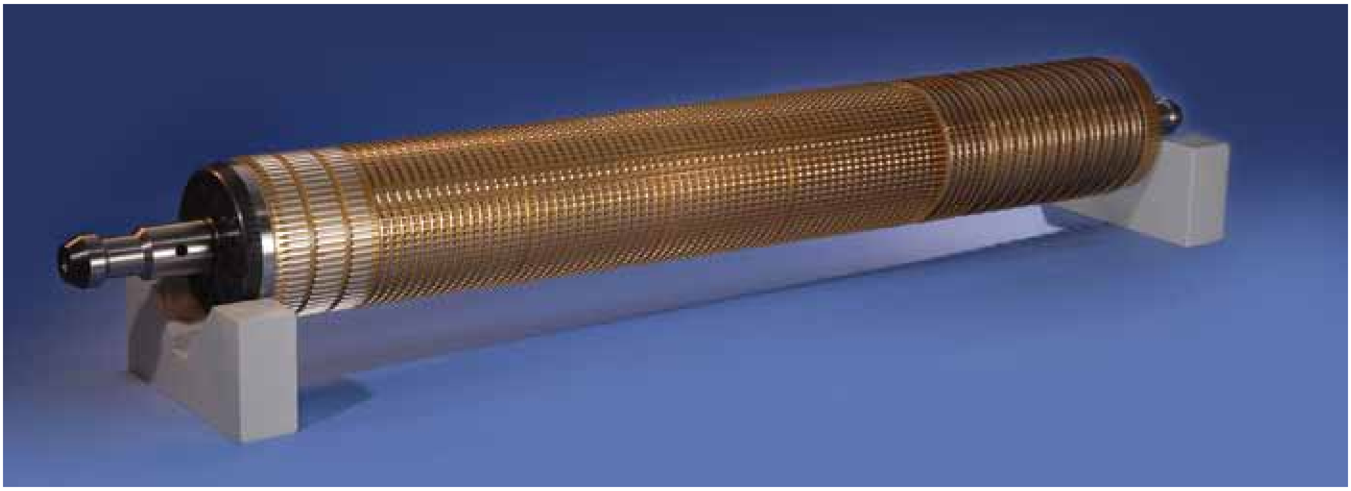
"Everybody grows up with lathes, mills and grinders," says Lee Egrin, CEO of Broaching Machine Specialties (BMS) in Novi, Michigan. "Every shop has that, but only one in a hundred shops has a broach. People are somewhat afraid. They cringe at broaching and don't even look at it. I find that when I finally break the barrier and I sell a man his first broach, he's back for his second in short order. Once they get into it and see how simple it is, they come back for more."

Matt Egrin, president of BMS, agrees. "Whenever we talk to anybody about buying a broaching machine and they're outfitting a building and putting in a whole machining line, they've ordered the grinder, they've ordered the lathe, they've ordered the material handling. The broaching machine is always the last thing they get to. Somehow we're always at the bottom of the totem pole."

"I think there's a fair segment of the market that has a bad taste in its mouth over the quality of broaching," says Scott Vian, vice president of Broachmasters Inc. and Universal Gear Co. in Auburn, CA. "But done properly, there's no process that will beat it for accurate size and speed of cutting. You can produce in seconds what it would take a gear shaper much longer to produce, and you'll probably end up with a better part. People are leery of the process, but the industry as a whole has come a long way."

One area of advancement in broaching technology is the introduction of CNC technology and better controls. Colonial Tool Group of Windsor, Ontario specializes in applying modern technology to older machine concepts. "We've upgraded all of that older technology with CNC and servo drives," says company president Brett Froats. "Many different parts can be programmed into the machine, so all you have to do is set up the part and push a button. In the old days, you'd broach a part, make some adjustments, and broach another part. There was a lot more trial and error."

"Uniform velocity and acceleration from the mechanical CNC provides for a better cutting action, resulting in improved tool life and accuracy," says F.J. "Butch" Wisner, vice president of engineering and marketing for Nachi America. "Mechanical CNC systems have significantly improved a broach-



Courtesy of Forst Technologie GmbH.

ing machine's flexibility. Today, if parts are similar in size and configuration, robot and vision systems can be used to perform automatic changeover, including broach bar and fixtures, providing for lights-off manufacturing."

In recent years, CNC controls have paved the way to the elimination of hydraulics and replacing them with servo drives and ball screws for many applications. These new electromechanical machines represent the wave of the future for many involved in the industry.

"Forst combines table-up machines with electromechanical drives to eliminate the hydraulic unit, which saves space and lessens the environmental risks," says Ulrich Salwender, vice president of sales for Forst GmbH in Solingen, Germany.

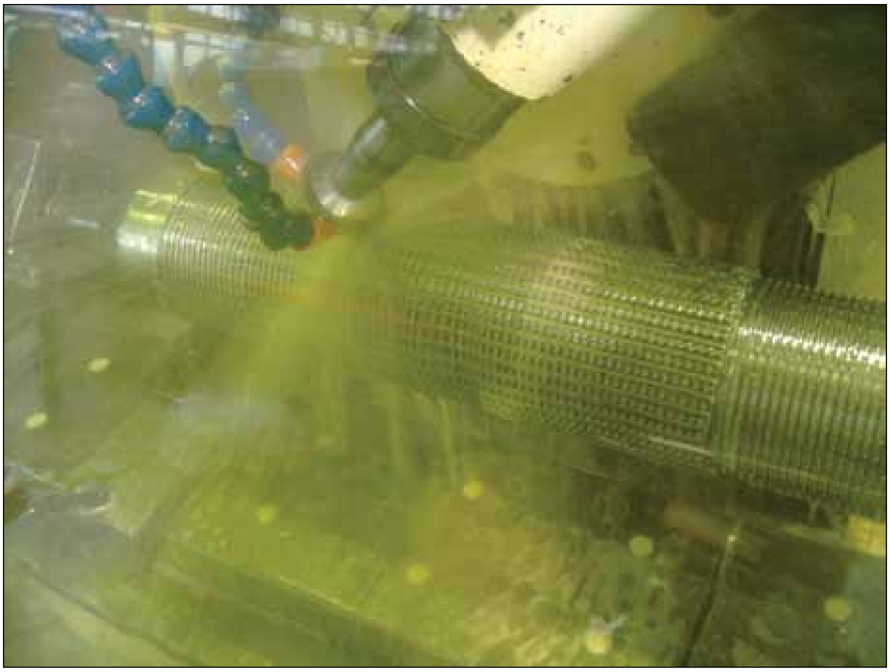
"We find the major advances to be in the electric drive machines nowadays," says Matt Egrin of BMS. "We've gotten away from the hydraulic drives. The majority of new machines the BMS builds today are electromechanical drives—servomotors driving a planetary roller screw or ball screw."

Egrin points to a number of advantages of electromechanical machines. Because there is no hydraulic cylinder and no oil compression, there's greater accuracy in the machine. "With an electromechanical machine, you've got a constant torque with no backlash, which results in a smoother cutting action, better part quality, better part finishes and better tool life."

The advantages of the electromechanical machine might lead to as much as a 30 percent increase in tool life, Egrin says, not to mention a much better surface finish.

"In some cases, we've been driven into electromechanical machines in order to make the required surface finish tolerances," Egrin says. "Someone will put a print in front of us, and it's got a considerably tighter surface finish tolerance than what you'd normally see in broaching. We figure those are best done on an electromechanical machine."

Ken Nemec, president of American Broach and Machine in Ypsilanti, Michigan, agrees that electromechanical machines are often the ideal solution. American Broach offers both hydraulic and electromechanical machines. "Generally speaking, the electromechanical machine is very desirable for many applications," Nemec says. But he also points out that electromechanical machines have their disadvantages as well.



CNC machine tool technology has allowed for more accurate production of broach tools. Courtesy of Colonial Tool Group.

One of them is that the high-end servomotors and ball screws are very expensive and often take much longer to order or replace. So if something goes wrong with an electromechanical machine, there's a better chance it will be out of service for longer than a hydraulic machine. Whereas hydraulic machine repairs are fast, easy and readily available, ball screws and other electromechanical components have notoriously long delivery times.

One way that machine builders combat this disadvantage is by stocking the service and repair parts. American Broach, for example, guarantees its customers stock replacement screws for its machines for a minimum of 10 years after the machine was purchased.

Despite the advantages of electromechanical machines, one area where hydraulic machines still rule is in bigger applications. "When you're getting into very high tonnage machines—say, over 60 tons—we probably stay with a hydraulic machine," Egrin says, but even that is changing. "As the motor technology increases, pretty soon you're going to make those high-tonnage machines with electromechanical drives as well."

Another technology that many broaching systems builders are taking advantage of is the increased capabilities offered by advanced engineering software. 3-D modeling software such as *Autodesk Inventor* helps these companies create broaching systems that can do more things and be delivered more quickly and reliably than ever before.

"Software gives you the possibility to design things you might not have taken on before," says Egrin. "Recently we developed a machine for a customer that actually had two different broaching axes. We were broaching parallel to the horizontal in one plane, and at a 45-degree angle on another plane. There was also a lot of automation, and a deburring station at the machine. This required a lot of out-of-the-box thinking. Whereas this would normally have required multiple machines, we were able to incorporate it all into one machine. Without the luxury of the advanced design software, that's something we might not have been able to design."

Wisner of Nachi adds that the advances in software allow for much less trial and error: "The ability to

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produce 3-D CAD and solid model simulation has significantly improved the first-time success rate for a newly designed broach tool. Historically, broaching has been an iterative process of continuous improvement."

The trend toward reducing setups and incorporating multiple functions in one machine seems to be a growing trend in the industry. "For years, we've been combining other secondary operations in our machines," says Steven Mueller, president of Ty Miles Inc. of Westchester, Illinois. "We're able to broach, drill, de-burr, tap a hole and perform other secondary operations along with broaching. For example, with a gear part, you might be pulling a keyway, but also drilling a timing mark into the part."

In addition to the increased flexibility and capability of broaching machines, broach tools have also improved. Better qualities of steel and more advanced coatings have resulted in tools that produce better parts and have longer tool life.

One of the areas where this is having a significant impact is hard broaching, says Ulrich Salwender of Forst. "Hard broaching with machines operating at 60-meters-per-minute has become a common process," Salwender says. "By re-broaching hardened components, distortions coming out of the heat treatment process are minimized and the surface quality is improved."

This capability has shown dramatic results in automated assembly lines where gears are press-fit onto shafts, Salwender says. The lines suffer from fewer stoppages caused by inadequate gear quality. In addition, hard broached internal splines press-fit onto shafts can transfer higher torque, because there is a better surface match and increased contact area.

Better tools also allow for processes such as dry broaching. "The cutting tools are made out of a higher grade steel and receive a special two-layer coating," Salwender says.

The greatest advantages are achieved when you put advanced cutting tools and modern machine tool technology together, Salwender says. "The combination of modern machine technologies and improvements of the cutting tools not only improved quality, productivity and cost effectiveness. It

Hard broaching allows for cutting of hardened parts after heat treating. Shown here are hard broaching tools and sample parts. Courtesy of Forst Technologie GmbH.

also gives the possibility of broaching materials that were not considered broachable before. One example is the large annulus gears in planetary gearboxes for heavy-duty applications like trucks, tractors, earthmoving equipment, wind mills, etc. In this lower-volume business, customers are trying to reduce the number of variants. With the increased volumes of now-broachable components and higher flexibility of our machines, broaching of such gears with straight or helical profiles replaces shaper cutting."

But despite all of the advances, creative approaches and efforts on the part of machine and cutting tool manufacturers, most agree that broaching is a shrinking industry, not a growing one.

The reason for that is the increased applicability of competing technologies. Powder metal parts, for example, can be designed with formerly broached features integrated into the part. Eliminating machining steps is one of the hallmarks of powder metal technology.

Also, many surface or external broaching applications can also be performed by milling machines or machining centers, and through better software and tools, those machines have also become more capable than ever before.

"The broaching business is losing applications where external machining is needed," Salwender says. "The development of high-speed machining technologies has increased the break-even point where broaching becomes profitable."

However, everyone we spoke with for this article was enthusiastic about the future of broaching. To those in the know, it's still the operation of choice for many applications.

"Broaching is still one of the fastest, most economical ways of removing material accurately," says Brett Froats of Colonial Tool. "There's no other process that competes with that."

"Broaching is still the most economically viable process for producing internal forms—gears and splines, for example," says Scott Vian of Broachmasters. "I don't think there's anything faster or better."

"Once a manufacturer invests, broaching produces a steady stream of quality parts for decades, with less effort than any other process," says Ken Nemec of American Broach.

"Speed and the number of pieces

continued

Modern broaching machines replace hydraulic systems with electromechanical systems, including servo drives and high precision ballscrews or planetary roller screws. Courtesy of Broaching Machine Specialties.

in the bucket at the end of the day are really what broaching is all about. Bottom-line, broaching is still a very efficient metal removing process," says Steven Mueller of Ty Miles.

Advanced automation, material handling and CNC controls represent the latest in broaching technology. Pictured here is a 50-ton, two-station CNC helical broaching machine from Forst.

Clearly, broaching has its believers. But perhaps Matt Egrin of BMS puts it best: "The perception of broaching is that it's an enigma. People don't understand it, so they're afraid of it. But it really is quite simple technology, and a very stable, repeatable process. Once you set that machine up, dial it in and run it for a few parts, it will run like that for thousands—tens of thousand—of cycles. You can make a lot of money running millions of parts off a broach, and it costs you hardly anything to maintain and operate the machine."

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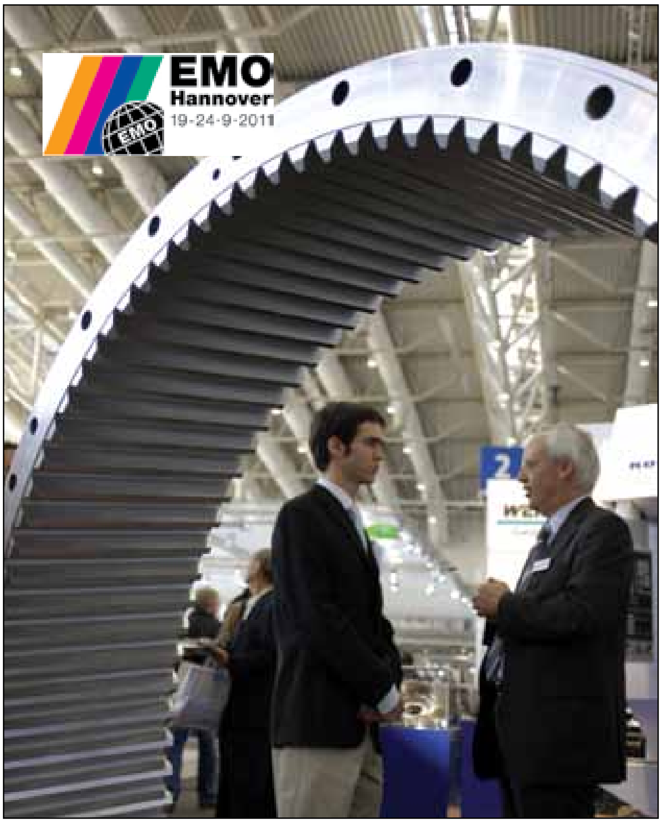
No Shortage of New Technology AT EMO HANNOVER



The gear cutting and precision gear finishing display area at EMO Hannover features an array of innovations and technologies (courtesy EMO Hannover).

Metalworking technology specialists will be front and center for six days at EMO Hannover 2011 (September 19–24). More than 2,000 companies from 38 countries will be on-hand to show off products and services, spotlighting their performance capabilities. This year's EMO Hannover is presenting its products and events under the motto "More Than Machine Tools." The trade fair puts special emphasis on machine tools, manufacturing systems, precision tools, automated systems, computer technology, industrial electronics and accessories and is sponsored by the VDW (German Machine Tool Builders Association). Here's a quick preview of some gear-related products on hand at the event:

Double-Spindle Honing Machine for Hardened Gears
Präwema (Booth # 0338)

The double-spindle gear-honing machine Synchrofine 205 HS D will be presented by Präwema for highly productive and flexible machining. This machine is specifically conceived for improving the profile and lead geometry of hardened gears. It is claimed to enable economical mass production with reduced secondary times specified as being only three seconds and incorporate all the advantages of the established single-spindle machine. What are already very short cycle times for the gear honing process are said to be further reduced. The unit is equipped with a newly developed Bosch-Rexroth MTX control system. A special highlight is seen in the measuring of workpieces in the machine, which serves to significantly reduce the times for changeovers and measurement. For more information, visit *www.praewema.de*.

Configurable System for Lean Gear Manufacturing
Felsomat (Booth # 0355)

As a systems supplier, Felsomat in Germany has reportedly adapted the complete technology chain for gear manufacturing based on innovative machine platforms and production methods to optimize flexibility, quality, throughput times and productivity. By adjusting soft machining, heat treatment and hard finishing cells to each other, customers are said to gain versatility, efficiency and reliability in their manufacturing. At the fair, the company will be displaying the new Flexline, a configurable manufacturing system for the complete production chain of gears, with standardized and configurable machines and new automation modules in intelligently combined soft and hard manufacturing cells. Together with Reishauer, visitors will be shown how they can achieve a sustainable advantage against their competitors. As the exhibitors insist, every process in the gear manufacturing chain is driven towards highest operating efficiency, whether turning, gear hobbing, laser welding, heat treatment or the finishing of gear flanks and other functional surfaces. For more information, visit *www.felsomat.de*.

Improvements for Hard Finishing Gears
Reishauer (Booth # 0353)

Reishauer claims to be setting standards in the hard finishing of gears by presenting a completely new range of products. The new line of machines is described as highly productive yet flexible, standardized yet configurable and innovative yet compatible with existing machines. In what is called a perfect interaction with company-produced tooling components, the new range represents a further leap in gear-grinding technology. In combination with a systematic parallelization of routines that enables an even further reduction of secondary machining times, the result is said to be superior productivity levels hitherto unattained. The spectrum of available options opens up a wide range of applicable technologies and tool systems. Thanks to standardized interfaces, the machines can be used as standalone versions, can be connected to a wide range of different automation systems, or can be fully integrated into the Felsomat Flexline cells. For more information, visit *www.reishauer.com*.

September 12–15—The Eleventh International Conference on Shot Peening (ICSP-11). South Bend, Indiana. ICSP-11 is a triennial conference and exhibition of the International Scientific Committee for Shot Peening. The commercial benefits of applying mechanical surface treatments are increasingly recognized, particularly in the automotive and aerospace industries. ICSP-11 will be an important international meeting for discussing the science, technology and applications of mechanical surface treatments. It will offer a unique forum, enabling scientists and engineers to deepen and update their knowledge of all aspects of mechanical surface treatments. The conference will cover a range of surface treatment topics based on technological aspects, process procedures, changes in the surface state, process simulation, service properties and fields of application. For more information, visit *www.shotpeening.org/ICSP-11*.

September 12–14—Interactive Manufacturing Experience (imX). Las Vegas. With a mission to advance U.S. manufacturing, imX is a collaboration of companies including DMG/Mori Seiki, Fanuc, Kennametal, MAG, Makino and Sandvik Coromant with organizations like the SME and the AMTDA to strategically address the challenges of traditional trade shows. Pairing high-level buyers and industry experts across U.S. manufacturing segments like aerospace, automotive, defense, medical device, heavy equipment, energy and green manufacturing, imX offers customized experiences, pre-set itineraries and a host of interactive and networking initiatives. This new approach signifies that as business climates change, business environments must also evolve. This interactive event will feature learning labs, VIP gatherings and industry panels. For more information, visit *www.imxevent.com*.

September 15–17—AWEA Small and Community Wind Conference. Des Moines, Iowa. More than 100 exhibitors will have the latest wind technology to show consumers, renewable energy professionals and installers how to best capitalize on wind technology for homes, farms and ranches, businesses and rural electric cooperatives. Community wind development has proven itself to municipalities, schools, universities and other groups willing to band together to produce their own energy. Designed with direct input from AWEA members who are shaping these important wind markets, this conference offers two tracks focusing on all the facets of the small and community wind industries. Hear from wind experts, investors and stakeholders from across the nation on how wind can create a cleaner energy future, strengthen regional and national economies and lead to a sound, profitable energy market. For more information, visit *www.awea.org*.

October 3–7—Basic Training for Gear Manufacturing. Richard J. Daley College, Chicago. This AGMA training course covers gearing and nomenclature, principles of inspection, gear manufacturing methods, hobbing and shaping. The course is intended for those with at least six months of experience in setup or machine operation. Classroom sessions are paired with hands-on experience setting up machines for high efficiency and inspecting gears. For more information, contact Jenny Blackford at *blackford@agma.org* or (703) 684-0211.

October 3–8—Detroit International Advanced Manufacturing Technology Show. Cobo Center, Detroit. The Detroit International Advanced Manufacturing Technology Show (DIAMTS) will focus on OEM auto parts and components, system and modules, green energy and electric vehicles and advanced CNC machinery and automation. Organized by the Detroit International Auto Salon and Detroit International Exhibition LLC., DIAMTS aims to bring the most advanced products and technologies to the region including machine tools, manufacturing systems and control equipment, electric vehicles, hybrid vehicles and auto parts and accessories. The trade show will provide an opportunity for local businesses to expand into the global automotive market, particularly in Asia. As the American auto industry continues to rebound with the estimated production of 15 million vehicles per year by 2014, DIAMTS is a networking forum to conduct business with the American automotive industry and its Tier 1 and Tier 2 suppliers. For more information, visit *www.diamts.com*.

DMG/Mori Seiki

EXPAND CAPABILITIES IN NORTH AMERICA

The Houston ribbon cutting ceremony included (left to right) Flanagan, Mohr, Kilty, Mori, Okada and Hooper (courtesy DMG/Mori Seiki).

DMG/Mori Seiki recently broke ground on a 200,000-square-foot factory to be situated on 14.5 acres in Davis, California. The plant will be Mori Seiki's first manufacturing facility in North America, and will employee between 100–150 personnel. At capacity, the new facility will produce as many as 100 units per month, focusing on the popular new X-Class line of precision machines. "Our initial targets are our horizontal machining centers—the X-Class NHX4000 and NHX5000 Series," says Mark Mohr, president of DMG/Mori Seiki USA. "Our next product under consideration is the DMU 50 and potentially other X class machines."

The plan of locating a new manufacturing facility in the United States is based on the possibility of the continuing decrease in the exchange rate between the United States and Japan. Dr. Masahiko Mori asserts, "If the value of the U.S. dollar declines, it will become fiscally advantageous to manufacture machine tools in North America, eliminating the cost of importing from Japan."

The addition of a new North American factory is expected to offset any disparity in the exchange rate between the two currencies and would ensure Mori Seiki customers the continued quality, precision and value they have come to expect in their machine purchase. Mori Seiki currently operates a total of four factories in the Nara, Mie and Chiba prefectures of Japan. The company's manufacturing presence in North America builds upon an existing overseas unit in Le Locle, Switzerland (DIXI Machines). Mori Seiki acquired DIXI in 2007 to manufacture and market products under the DIXI brand, but also to expand its capacity in order to manufacture and sell Mori Seiki branded products.

Manufacturing in the United States enhances the company's existing infrastructure in North America. Engineering operations are already established at the Digital Technology Laboratories (DTL) in Davis, California. Software and machinery has been designed at DTL since 2000, when the group was launched. Today, the group boasts over 80 employees; the creation of a North American manufacturing plant creates further opportunity for R&D collaboration in the United States. The Davis, California site offers several other advantages as well. "The West Coast location makes it very easy to work with our Japanese colleagues," says Mohr. "For instance, we will be importing ball screws and spindles from our own manufacturing facilities in Japan—not for purposes of cost saving, but because they're simply the highest quality." The nearby UC-Davis and Berkeley campuses ensure that the available workforce is also top-quality; the area is regarded as a proving ground for the latest advances in technology, engineering and computer sciences.

Mori Seiki remains focused not only on R&D and production, but also on installation and proper maintenance. Mori Seiki's recent launch of the Mori360 Total Support package in the United States and Canada highlights the company's commitment to complete customer service. The addition of the new North American factory will raise Mori Seiki's total monthly output capacity by approximately 100 units to slightly more than 900, preparing Mori Seiki for the anticipated global expansion of machine tool sales in the coming decade. Construction is slated for completion in fall of 2012.

A dedication and ribbon-cutting ceremony also took place in June to mark the opening of a new joint technical center in Houston between DMG/Mori Seiki and Ellison Technologies. The official, three–day grand opening event of the technical center followed, with visits by more than 500 attendees. The 22,500-square-foot facility is one of the largest of Ellison's 21 locations across the United States and Canada and includes a full staff of over 25 service, application and sales engineers, including engineering support staff from DMG/Mori Seiki USA.

Machine demonstrations and technical seminars focused on big technology—specifically for the application of large machines like the NT6600DCG integrated mill turn center, DMU 125 FD duoBLOCK universal milling machine and the NZL6000 two-turret lathe. Seminars were presented on new oil and gas machining strategies, as well as increasing productivity through employee education and training. The 6,500 sq ft showroom was designed to demonstrate the latest in DMG and Mori Seiki technology and advanced machining

continued

processes. Future visitors will be able to see live demonstrations on industry-specific technology emphasizing process optimization, testing and development. The facility also features a state-of-the-art training and media area for customer seminars, product demonstrations and training sessions. This area was utilized by more than 30 partner suppliers during the grand opening event, bringing opportunity for visitors to collaborate with multiple experts in one, convenient location. Ellison Technologies and DMG/Mori Seiki support engineers will continue to provide total customer support from the new Houston facility location by offering engineering services including test cuts, turnkeys and accessory integration. Customer service is further enhanced by the nearby DMG/Mori Seiki Dallas Technical Center and its inventory of over $125 million in spare parts.

"DMG/Mori Seiki and Ellison Technologies remain focused on continuing to provide exemplary customer support in all areas: R&D, technology, education, service, parts and partner products," Mohr says. "With that goal in mind, we are pleased to expand our services at the Houston Technical Center and look forward to continuing to meet and exceed customer expectations."

Robert Errichello

LEADS DIVERSE GEAR EXPO LINEUP

Robert Errichello with his "Gear Muse" Corny.

Robert Errichello from Geartech will present "How to Organize and Manage a Failure Investigation" at Gear Expo 2011 in Cincinnati (November 1–3). Attendees will learn techniques for organizing and managing a failure investigation, including identifying the failure mode and the root cause and recommending repairs or improvements. Errichello is a longtime *Gear Technology* technical editor and is considered one of the foremost experts in machine design, fracture mechanics, vibration and material science and helped introduce the world's first gearing standard for wind turbines, among many other achievements. For 20 years, Errichello has taught one of AGMA's most popular courses — the Gear Failure Analysis seminar. During his long career, Errichello's clients have included many major corporations around the world. In fact, over 40 wind turbine companies have turned to Errichello for his gearing expertise. In addition to the Failure Investigation session, Gear Expo offers an affordable, respected, gear-specific curriculum to keep you fresh and up to date in the current competitive landscape. Program topics include: AGMA's Fall Technical Meeting, Training School for Gear Manufacturing, Why Bearings Fail, Materials Selection and Heat Treatment of Gears, Fundamentals of Gear-Health Monitoring and ASM Heat Treating Society sessions. For more information, visit *www.agma.org*.

ALD

FORMS TECHNOLOGY RELATIONSHIP WITH DIBALOG

Vacuum furnace manufacturer ALD-Holcroft of Wixom, Michigan recently announced a newly formed technology relationship with the energy management company Dibalog USA Inc. of Simpsonville, South Carolina and the parent company Dibalog GmbH of Heidelberg, Germany. The vacuum furnace manufacturer can now offer integration of energy management through the expertise and experiences of Dibalog. Dibalog offers customized systems for energy optimization and data logging. "Our large, ModulTherm systems and single chamber furnace installations can benefit from the Dibalog know-how as they drive the cost of operation down," says Bill Gornicki, vice president of sales for ALD-Holcroft. "Finally, an expert solution to the issue of high cost electricity."

For more information, visit *www.ald-holcroft.com*.

Metal Powder Industry Rebounds

The North American powder metallurgy (PM) industry regained its growth momentum in 2010 after five dismal years of declining demand, reported Michael E. Lutheran, president of the Metal Powder Industries Federation (MPIF) at PowderMet2011. While the dramatic rebound can be largely pinned on the increase in light-vehicle sales, other end markets also gained, he stressed. PM's design-engineering advantages, contributions to sustainability, and proven economies are stronger than ever. The industry's real turnaround actually began during the last quarter of 2009, when customer inventories were at their lowest point and the pipeline needed refilling. This situation signaled a firming of demand for metal powders and PM parts. A clear indicator of rising production levels was the hiring spurt seen at many PM parts fabricator plants.

Total 2010 North American metal powder shipments increased about 35 percent to an estimated 451,021 short tons. Total iron powder shipments in 2010 soared by 44.23 percent to 353,121 short tons. The PM parts share represented 315,192 short tons, a 50 percent increase over 2009 levels. Lutheran pointed out that 2009 was a dismal year and the increase brought the industry to levels still below its peak year of 2004, when iron powder shipments hit almost 474,000 tons. "Nevertheless, we are back on the growth track, regaining momentum in nearly every quarter," he said. For more information, visit *www.mpif.org*.

Manufacturing Tech Suppliers

APPLAUD ADVANCED MANUFACTURING INITIATIVE

Douglas K. Woods, president of the Association for Manufacturing Technology (AMT), greeted news of the Obama administration's launch of its Advanced Manufacturing Partnership with optimism that the U.S. government is finally realizing the important role manufacturing technology plays in national security and sustained economic growth. "AMT is encouraged by the administration's continued focus on the manufacturing sector," Woods says.

The Advanced Manufacturing Partnership is a national effort to bring industry, universities and the federal government together to invest in emerging technologies that create manufacturing jobs and boost global competitiveness, particularly in industries critical to national security. The $500 million plan uses existing funds and future appropriations from various federal agencies to boost innovation in manufacturing technologies such as small, high-powered batteries, advanced composites, metal fabrication, bio-manufacturing and alternative engineering. The goal is to enhance defense-critical industries; build U.S. leadership in next-generation robotics; increase energy efficiency in manufacturing; and develop technologies to help improve manufacturing efficiency.

"Collaboration is key to speeding the development of next-generation manufacturing technologies and products, as well as building a manufacturing smartforce," Woods says. "Leveraging existing funds to jumpstart this effort is a big plus given the current deficit. However, as Congress grapples with the debt ceiling and budget this summer, it must consider that investments in science, technology and smartforce made today will increase revenue in the long-run. As the representative for U.S. manufacturing technology suppliers, AMT is eager to work with the stakeholders on this important collaborative effort to regain worldwide leadership in manufacturing," Woods concluded. For more information, visit *www.amtonline.org*.

Nordex

COMPLETES LARGEST COMPANY WIND PROJECT

Delivering on the potential that the American market holds for the wind industry, Nordex USA, Inc. announced completion of the largest project ever undertaken by Nordex Group. The 60 N90/2500 wind turbines at Cedar Creek 2 are commissioned. The logistical challenges of preparing and delivering a project of this size are significant. If the blades and towers for the project were placed end-to-end, they would stretch for 8 miles (13 km).

The wind farm, 20 miles north of New Raymer in Weld County in northeastern Colorado, is jointly owned by BP Wind Energy and Sempra Generation. The power produced by this 150 MW project, enough to supply 45,000 American homes, has been purchased by Public Service Company of Colorado, an Xcel Energy company, under a 25-year agreement.

"We are pleased that BP chose Nordex turbines for Cedar Creek 2, one of the largest projects in Colorado. Our relationship with BP dates back to 2002 when Nordex first supplied turbines to one of their refinery sites in the Netherlands," commented Ralf Sigrist, president and CEO of Nordex USA, Inc. "As a growing global company, it is important for Nordex to build on its connections with existing customers to continue our expansion in America."

Nordex was responsible for the turbine supply and commissioning and will continue to provide service and maintenance under a five-year contract. The mile-high altitude required some special adaptations, including increasing the turbines' heat exchanging capacity. Nordex has both completed and current American installations totaling 500 MW in several states, including Minnesota, Pennsylvania, Wisconsin, Maryland, Iowa and Idaho. For more information, please visit *www.nordex-online.com*.

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6) What is your primary job function responsibility? (Check one)

- ❑ Corporate Executives (B)
- ❑ Manufacturing Production Management (C)
- ❑ Manufacturing Production Department (D)
- ❑ Manufacturing Engineering Management (E)
- ❑ Manufacturing Engineering Department (F)
- ❑ Product Design, R&D Management (H)
- ❑ Product Design/ R&D Personnel (I)
- ❑ Purchasing (L)
- ❑ Marketing & Sales, Communications (M)
- ❑ Quality Control Management (P)
- ❑ Quality Control Department (Q)
- ❑ Other (N) ______________

7) How is THIS LOCATION involved in the gear industry?
(Check all that apply)

- ☐ WE MAKE GEARS (or Splines, Sprockets, Worms, etc.) (20)
- ☐ WE BUY GEARS (or Splines, Sprockets, Worms, etc.) (22)
- ☐ WE SELL NEW MACHINES, TOOLING OR SUPPLIES TO GEAR MANUFACTURERS (24)
- ☐ WE provide SERVICES to gear manufacturers (25) (please describe) ______________
- ☐ WE distribute gears or gear products (including agents and sales reps. (26)
- ☐ WE are a USED MACHINE TOOL dealer (30)
- ☐ Other (please describe) ______________ (32)

8) Which of the following products and services do you personally specify, recommend or purchase? (Check all that apply)

Machine Tools

- ☐ Gear Hobbing Machines (50)
- ☐ Gear Shaping Machines (51)
- ☐ Gear Shaving Machines (52)
- ☐ Gear Honing Machines (53)
- ☐ Gear Grinding Machines (54)
- ☐ Gear Inspection Equipment (55)
- ☐ Bevel Gear Machines (56)
- ☐ Gear/Spline Roll-Forming Equipment (57)
- ☐ Broaching Machines (58)
- ☐ Heat Treat Equipment (59)
- ☐ Deburring Equipment (60)
- ☐ Non-Gear Machine Tools Turning, Milling, etc.) (61)

Tooling & Supplies

- ☐ Functional Gages (62)
- ☐ Workholding (63)
- ☐ Toolholding (64)
- ☐ Cutting Tools (65)
- ☐ Grinding Wheels (66)
- ☐ Gear Blanks (67)
- ☐ Lubricants/Cutting Fluids (77)

Service & Software

- ☐ Heat Treat Services (69)
- ☐ Gear Consulting (70)
- ☐ Tool Coating (71)
- ☐ Tool Sharpening (72)
- ☐ Gear Design Software (73)
- ☐ Gear Manufacturing Software (74)

Power Transmission Components

- ☐ Gears (75)
- ☐ Gear Drives (76)
- ☐ Bearings (78)
- ☐ Motors (79)

9) What is the principal product manufactured or service performed at **THIS LOCATION?**

____

10) How many employees are at THIS LOCATION (Check one)

☐ 1-19 ☐ 20-49 ☐ 50-99 ☐ 100-499 ☐ 500+

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Doodling With Metal

Inside the Mechanical Mind of a Gear Artist

When Justin Gates stares at a group of small gears he may see a bird or a tree or a flower. "Generally, I don't start with an idea. I'll pick up a couple of gears and see how they look together. I'll pick up another couple and see how they work with the others. I suppose it's a kind of doodling, just with metal. Sometimes I will have an idea going into it that just works. The metal gears' roundness oddly seems to favor the organic in my case."

The 31-year-old self proclaimed nomad—he's lived in Florida, Georgia, Washington and now Illinois—grew up with a gearhead father that worked on cars and a grandfather who was a railroad mechanic. "With these two, there were always mechanical bits lying around to pick up and play with, and they instilled in me a curiosity for how things work. I've always found gears, wheels and cogs incredibly beautiful in their design and how they mesh together."

Gates, a Northeastern Illinois University student and freelance sculptor/artist says the idea for gear jewelry came from this perceived beauty. He taught himself how to solder and created four pendants out of some watch gears for his wife and her family. "They liked them so much that they told me I should start selling them."

"One can find mechanical parts as decorations all over my house," he adds. "I have bent railroad spikes on a window sill, an old rusted industrial grate as a centerpiece over my desk and a collage of large machine gears on my wall. Basically, if it rusts, it has a place with me. It's a dream of mine to one day work on larger installations with gears as the focal point."

Gates purchases large lots of old and worn out mechanical watch movements from places like Ebay or Etsy. He has also received old watches from friends, family and complete strangers that just enjoy his work. "At a recent fair, I was asked by several people if I take old watches, and my answer as always is yes. Having always thought of myself as an artist, it's great to finally have an outlet to show people my work."

This work, including gear-themed necklaces and earrings, is of particular interest to the steampunk community. "I receive feedback from those in the community that my work is quite different from what they've seen," Gates says. "It's lighter, more delicate, or more airy than most works out there. Where normally one would find an entire watch movement made into a pendant or ring, I take the time to disassemble that movement and rearrange it into something that is completely different and new... sort of breathe new life into old parts."

Thanks to this slight difference, Gates likes to call his work, "not quite steampunk" so he's not upsetting an established community he feels already has plenty of great artists. He's thankful for being an artist in the digital age where he can get his work out to the masses without the need for large, elaborate marketing campaigns.

"As much as I sometimes deride the Internet, it's great to live in an age where millions of people from around the world can view and give feedback to something that I've created," Gates says. "For me, more than anything it's getting the messages of appreciation that really makes all the burned fingers and strained eyes worth it."

Those interested in learning more about Gates' gear-themed artwork can visit *www.amechanicalmind.etsy.com* or *www.amechanicalmind.co*m. The latest pieces in his collection can also be viewed at *www.facebook.com/amechanicalmind.* Gates will be attending Ravenswood Remix, a recycled art fair in Chicago on September 3–4.

Shade Tree Descendant

Thunder Mechanism

Gearrings

Wildflower