GEAR TECHNOLOGY

JANUARY/FEBRUARY 2006

The Journal of Gear Manufacturing

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THE OTHER SIDE OF THE WORLD

- Strategic Partnerships & Overseas Ventures
- Gear Manufacturing in the Far East

TECHNICAL ARTICLES

- Simulation of Face Hobbing
- Hypoid and Spiral Bevel Assembly
- Noise & Vibration of Planetary Gear Drives

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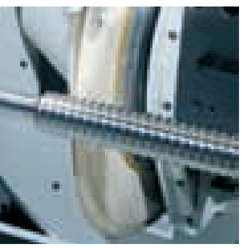
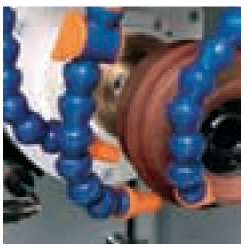









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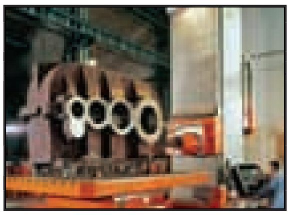
JANUARY/FEBRUARY 2006 *The Journal of Gear Manufacturing*

THE OTHER SIDE OF THE WORLD



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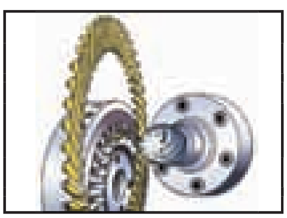
TECHNICAL ARTICLES



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GEAR TECHNOLOGY
The Journal of Gear Manufacturing

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Keep Those Letters Coming

In the past, we have often asked readers to let us know what they were thinking. We've requested your input and feedback on a number of topics over the years. But this past issue, we must have struck a nerve.

About a dozen of you wrote in with reactions to my editorial, "Is Gear Expo Worth It?" which appeared in the November/December 2005 issue. Some of those letters appear on the pages following this one.

I was glad to see some of the leaders of AGMA and exhibitors write in support of the show. They, like me, see a lot of value in the show for our industry. But I was also glad to hear from a number of leaders at major gear manufacturing companies. These are the very people who should be the attendees of Gear Expo, and they have concerns, like I do. I expect that some of their comments should provide food for thought for the AGMA leadership.

I imagine there are many more of you out there who had strong feelings on this subject but didn't respond. I'd still like to hear from you. The people who manage Gear Expo need to hear what you have to say. If you attend the show, why is it valuable to you and your company? If you don't, why not? What can the show's managers do or offer that might interest you in the future? What could be done better? Would a different city or time of year be more suitable?

For nearly 22 years, *Gear Technology* has served the gear industry, and we are here to provide a forum for you. We'll continue to provide a place for the exchange of ideas, but we need your participation. So keep sending those cards and letters—not just on Gear Expo, but on any subject that concerns you.

For example, I'd love to hear your comments and reactions to this issue's feature topic: Gear Manufacturing on the Other Side of the World. I'm sure many of you have relevant experiences to share, as well as opinions or perspectives about the increasingly global nature of our industry. All of us will benefit from sharing that knowledge and insight.

A forum only works if there's participation from its members. In our case, that's you, our readers. Your reactions to last issue's editorial are a good start. Continuing the discussion on Gear Expo is in the best interests of the show and our industry. As always, we'll do our best to provide you with thoughtful, interesting and relevant articles that should give you something to react to. The rest is up to you.

Send your Comments To:
Letters to the Editor
Gear Technology
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Elk Grove Village, IL 60007 USA or
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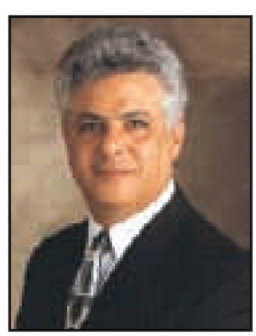

Michael Goldstein, Publisher & Editor-in-Chief

Is Gear Expo Worth It?

Readers Respond

Want to respond to something in this issue of *Gear Technology*? Send mail to:
Letters to the Editor, *Gear Technology*
P.O. Box 1426, 1425 Lunt Ave.
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E-mail *publisher@geartechnology.com*

Michael:

Thank you for one of the more honest appraisals I've read from any magazine publisher in a long time.

The questions you've raised regarding the viability of the Gear Expo are dead on. The industry needs to take a hard look at whether it can continue to support a single-product trade show in a market-driven economy that forces consolidation at all levels. At this point I believe that the costs outweigh the benefits.

Philadelphia Gear Corp. is 115 years old. We are a founding member of AGMA. We are bullish about the gear industry, the competitiveness of U.S. manufacturing and the overall short-term economic outlook. But the reality is that I will only spend marketing dollars to put us in front of my end-user customers providing solutions—not where machine sellers are exhibiting. This sometimes means more regional shows—more direct sales and other media vehicles.

If we want to buy equipment, we have established used equipment networks, and the Internet lets us all access the very few remaining high quality gear machine makers left in the world. Other industries may not yet have this problem, but the gear industry is smaller than it once was both in real terms and relative to other industries. I agree with you that we would more likely go to EMO to see new equipment because we could also see other machine tools that might be of interest. Take into account that many of the Gear Expo no-shows will never care about making gears for the automotive industry and it's probably time to start thinking about consolidating with another related trade show.

Regarding AGMA, I believe that there are still very real benefits from collaborating on industry technical and international standards.

Bottom line. In the 1980s we probably all attended at least one meeting where you 'crammed' one day's worth of work into four days at some resort. Those days are gone. Time is precious. It's not an owner's club any longer. Regardless of your size, it's tougher, more global and more relentless, and each company has to be thinking hard what its strategy is all about and how its limited resources are spent.

Carl D. Rapp, President and CEO
Philadelphia Gear Corp.

Dear Michael:

The management at Chicago Gear agrees with your recent Publisher's Page.

For years many of us at Chicago Gear have felt AGMA is on auto-pilot. So much of AGMA's effort is put toward a revenue generating agenda, so little toward helping members be better manufacturers, helping them sell gears and thus becoming a better gear company.

I feel that AGMA can become a strong tool for U.S. manufacturers. It could help companies be more aware of new markets, hot markets and ways to manufacture products more efficiently.

Instead, it seems a disproportionate amount of their efforts are put toward the engineering and design side. Not to say that the standards are not important—we use AGMA standards on a regular basis.

But once AGMA starts to work with member companies as a force to retain existing markets and find new, we believe their membership will grow. It's like we get the same old product each and every year.

It would be easy for us to demand change. How about changing the way we think? I believe that AGMA should consider its members its customers. Believe me, we work every day to do all we can to make our customers happy.

Thank you very much for your article. We appreciate your thoughts.

Sincerely,
Wayne Wellman, CEO, and Frank Romans, President
Chicago Gear-D.O. James Corp.

Michael:

I take exception to your November/December Publisher's Page editorial. Like a lot of polls, it always depends on how the question is framed. I, too, polled quite a few exhibitors—those with 10 x 10 foot booths all the way up to the biggest exhibitors of the show. I must say that their experience mirrored that of ours: It was an "excellent experience."

There are a variety of ways to qualify a show. Counting heads is one, but it alone may not tell the whole story. We at Reishauer look at it differently, and the question that begs to be asked is, what would we have missed had we not exhibited? That's an easy one to answer. I kept hearing the same theme from all of the exhibitors I spoke with: "It's the quality of the visitor," not the quantity. As everyone knows, only a small number of those involved in the manufacturing process do the actual buying. If you have the right people, it's not rocket science—they come to buy!

As far as I'm concerned, if asked what the cost to attend Gear Expo was, my answer would be ….Priceless!

I'm sure there will be a few who said they had a poor show experience. To those I would say that the success of a show largely depends on the level of effort you put into it.

Dennis Richmond, Vice President
Reishauer Corporation
(Editor's Note: Dennis Richmond will take over as chairman of AGMA's trade show advisory council in March.)

Dear Mr. Goldstein,

I agree whole-heartedly with your comments made in the November/December issue of *Gear Technology* regarding Gear Expo. A couple of years ago, I provided comments to AGMA regarding the show, the future of this type of exposition, and suggestions regarding how it might be made more beneficial to attendees as well as exhibitors.

Fairfield Manufacturing participates in a number of trade related shows annually, both domestic and global. We have seen the OEM visitor/customer participation for trade shows in general decrease with the added forms of communications (web sites, e-mail campaigns, and related electronic media). The technical trade show community has gone through somewhat of a consolidation and merging process where component trade organizations have merged or co-located with larger shows that feature OEM exhibitors.

Examples are CONEXPO, BAUMA, Intermat and others, where organizations such as the National Fluid Power Association (NFPA), have co-located within the shows and broadened the visitor base dramatically.

I have felt that strong consideration should be given by AGMA to co-locate within another larger show forum, (perhaps the Manufacturing Show in Chicago or other). It is very apparent that AGMA is not large enough to garner the broader and larger scale of attendees required to warrant its own exposition. Fairfield attended the 2005 show purely to show support for AGMA and received little otherwise from the show. I hope to see us wise up and make the necessary changes to provide the membership with a more meaningful exposition and presence.

John W. Strickland, Director, Marketing & Product Development
Fairfield Manufacturing Co., Inc.

Dear Michael:

Yes, Michael, Gear Expo is worth it! Your "Publisher's Page" editorial in the November/December 2005 issue of *Gear Technology* asked for comments. On behalf of AGMA's Board of Directors, I am happy to send the Board's comments in this open letter to you and to *Gear Technology*.

Over the last two months, along with a number of the AGMA board members, I have been able to review carefully the results from the 2005 event as well as earlier shows. Gear Expo is an important event to AGMA and to the gear manufacturing industry in North America and the world. As with all major activities of the association, the board does not wait until the moment of the event to take stock and recommend action. Over the last two years, the board and staff have analyzed Gear Expo and have restructured it in a number of ways that played a part in 2005's success.

Attendance: Our objective was to attract to the show qualified decision makers and advisors who could make buying decisions for their companies. The numbers can be sliced and diced, or they can be compared to straw men to imply that what didn't happen was more important than what did. But, in the end, every exhibitor knows that sales on the floor, inquiries after the show and continued future business—even a year or two after the exhibit—are the real measures of the effectiveness and success of Gear Expo. From unsolicited comments to the formal survey of exhibitors conducted following the show, an unprecedented number of exhibitors met or exceeded their objectives.

One last word on attendance: The number of companies and employees working in this industry has been declining for years. As Dr. Michael Bradley, AGMA's economic counsel, detailed in his presentation in the Solutions Center, employment in the U.S. gear industry has declined since the 2001 and 2003 shows so that today, the industry employs approximately 12,400 people, of whom, about 9,000 are production workers—employees who have relatively little say in major purchasing decisions.

Registered visitors and registered exhibitors, that is the show attendance, numbered over 2,600, interestingly close to the number of non-production workers in the industry.

Solutions Center: The Solutions Center was a first-time endeavor, added because of research on visitor opinions conducted after the 2003 show. The Solutions Center was a definite success. Our objective in establishing the Solutions Center inside the exhibition hall during exhibit hours was to add an additional educational activity that would benefit visitors and exhibitors "during exhibit hours." With over 300 total attendees and each session averaging 14 attendees, we met that objective.

Of course, the exhibitor/presenters experienced varying levels of interest, as one would expect. The good news is that every session, except one, attracted between 7 and 60 attendees; the average was 14.5 and the median was 11.

Education: As was clearly detailed in the research results, visitors wanted more educational programming at the show. We worked with several allied industry associations to provide increased access to technical information for the attendees. Moreover, we positioned the AGMA's Fall Technical Meeting to coincide with the show.

Networking: I cannot overstate the importance of networking to the value of Gear Expo. Indeed, on your Publisher's Page in the issue of *Gear Technology* immediately following the 2003 Gear Expo, you wrote, "For four days, Gear Expo provided access to the greatest collection of knowledge and experience regarding the manufacture and processing of gears anywhere on the planet." That was also true for the 2005 Gear Expo.

With the shrinking size of the domestic gear industry and the changing dynamics of the global economy, networking is even more compelling as a means of keeping up with one's peers, customers and competitors.

Michael, it is always tempting and dangerous to look to one indicator as the measure of success of a complex event. Exhibitors and attendees participate in Gear Expo for a variety of reasons and objectives. Fortunately, AGMA's board of directors is a diverse group of members whose products, business models and locations reflect the range of members in the association and the industry. We know there is work to be done on Gear Expo, but we also know that the 2005 show was successful for AGMA and for the industry we represent.

I look forward to seeing you at the 2007 Gear Expo!

Sincerely,
Leslie Hennessy, AGMA Chairman

Dear Michael:

In the last two months since the AGMA held its bi-annual gear manufacturing trade show in Detroit, Michigan, discussions have occurred regarding the value of this show. I would like to express my opinion on this show and equally importantly my view of the changing manufacturing and marketing environment in North America.

First, manufacturing in North America has changed and will continue to change. At one time, the single most important customer group for our business was the electric power tool industry. A majority of these manufacturers of drills, saws, etc. are just completing their move to China or other countries with low operating costs. This is just one example of how the manufacturing of products has permanently changed. I am sure that others have their own experience, perhaps in the automotive sector. These changes have required our company to refocus on how, where and what we market and have resulted in our becoming a "lean" marketing organization. The old standard paradigm of marketing does not work anymore and I challenge every organization to adapt to a new marketing design.

Second, all trade shows have changed. The AGMA Gear Expo peaked in 1997 with 4,148 registrations and at the 2005 show there were 2,644 registered attendees. This is a decline of over 1/3, but it is exactly the same as is being experienced by other manufacturing trade shows. One criticism constantly being raised is the counting of exhibitors as part of the attendance numbers. Peter Eelman, Vice President of AMT recently stated that "Virtually all shows count total registrations. That means visitors and exhibitor personnel." This counting technique is common for all shows.

On a positive note, we had the most successful AGMA Gear Expo show in the twenty-year history of our company. Not only did we sell machines directly off the show floor, but we booked orders for other equipment during the show. This buying has continued after the show. How did we do it? We prepared before the show with a mailing of nearly 5,000 premium full color brochures that showed what we would be displaying. We arrived with proper planning and objectives. We brought "iron" to the show, and a lot of it, for the customers to "kick-the-tires." We received many comments that our booth was continuously busy with customers. Would you spend your company money without seeing some smoke and chips? I wouldn't.

The AGMA trade show also gives positive support to our industry in many other ways. Quoting Michael Goldstein of Gear Technology, "…Gear Expo provides the greatest collection of gear knowledge, experience and expertise anywhere in the world." This is perhaps the greatest opportunity for "gear" networking and the chance to meet the people of our industry. Gear Expo is truly the ultimate gear education experience! Another very important aspect of this show is that it contributes financially to the AGMA, and in turn, this allows the AGMA to directly support our gear manufacturing industry with a variety of activities.

No, the AGMA Gear Expo isn't perfect, but you can count on my support, participation and positive contribution to improve this show for the future. Come meet us and see our equipment at the Koepfer America booth, AGMA Gear Expo 2007 in Detroit, Michigan.

Dennis Gimpert, president, Koepfer America L.L.C.
(Editor's Note: Dennis Gimpert is also chairman of AGMA's Business Development Executive Committee, which oversees Gear Expo.)

Finish Hobbing Crowned Helical Gears without Twist

A machine operator mounts a gear blank in a hobber. A few moments later, he removes the workpiece, a crowned helical gear that has been finished, deburred and chamfered—and that has no twist.

This combination of operations is possible using a new product available from LMT-Fette Inc. The product is a tool system that consists of a roughing hob, a set of deburring and chamfering tools, and a finishing hob, all mounted on one arbor.

The finishing hob is the tool that removes twist from gears. Called a "twist-free hob," the tool was designed for high-volume production of the same or similar gears. Jointly developed by the Liebherr Group and Fette, the tool can be made to hob external spur or helical gears without twist, also called profile bias.

Twist is a defect that can result in more gear noise and less load carrying capacity. The defect is caused by large tapers or crowning, especially on helical gears. Twist occurs on both spur and helical gears, but it's negligible on spurs.

In the past, twist was corrected via finishing operations. "This correction has been done in grinding for a while," says Reinhold Cordella, a regional sales manager for Liebherr Gear Technology Inc. in Saline, MI. Other finishing methods for removing twist included shaving and honing.

The twist-free hob, however, eliminates the defect via its modified profile and its diagonal movement across gear teeth. The hob's modification is a gradient change in its profile. This change is synchronized with diagonal hobbing so the tool can both finish hob and compensate for twist in the same operation.

In principle, the twist-free hob can be used on any hobber capable of diagonal hobbing, says Oliver Winkel, application engineer–gear cutting for Liebherr Verzahntechnik GmbH of Kempten, Germany.

During operation, the hob head swivels to different angles to rough hob, to deburr and chamfer and to finish hob, so the lead and helix angles are correct for the two hobs and the lead angle is also correct for the deburr-chamfer tools.

To speed up this process, the hobber should have a quicker-than-usual A-axis, Winkel says. He adds that hobbers can be retrofitted so the A-axis can achieve the necessary speed.

The tool system can accommodate its three tools via the twist-free hob. That tool is a shank-type hob with an integrated arbor. A roughing hob and a set of Fette's Chamfer Cut tools can then be mounted on the arbor.

The tools were combined on one arbor to increase production efficiency. They were also combined to save money on separate machines for deburring, chamfering, grinding or shaving and to save money on shaving tools and grinding wheels.

Manufactured by Fette, the twist-free hob tool system was introduced in September, at EMO Hannover in Germany, on a Liebherr hobbing machine with direct drive technology. A month later, Fette exhibited the tool system at Gear Expo 2005 in Detroit, MI.

The set of Chamfer Cut tools can be made to deburr and chamfer either external spur or helical gears. The tools deburr and chamfer the roots and side edges of gear tooth flanks. To use the tools, a hobber needs tool spindles able to turn in both directions and special software from the hobbing machine's manufacturer.

However, gear manufacturers need large shifting ranges on their hobbers to use the Chamfer Cut tools. The tools reduce shifting ranges, thereby reducing hob efficiency, so Winkel suggests hobbers with shift ranges of 180–300 mm. That way, the machines aren't as affected as ones with smaller ranges.

Like other roughing and finishing hobs, this tool system can save gear manufacturers' money compared with the cost of using a hob for both roughing and finishing in a two-pass hobbing process. The savings come from increased tool life for both the roughing and finishing hobs.

Specifically, the two hobs can be designed independently, so each has the optimal number of threads, number of gashes and specific tooth design. Consequently, the roughing hob can be designed for optimal cycle time without worrying about the workpiece's final profile quality. Also, the roughing hob has a longer life in production use than a combined roughing and finishing hob.

"The roughing tool can be used to normal wear points without having to stop production and recondition the tool when the quality of the finished profile would be in question," says Darryl Witte, product manager–gear tools for Fette's operation in Cleveland, OH.

Moreover, the finishing hob can be optimized to create a quality profile and can be made of alternate material to increase hob life. As Witte says: "The finishing tool far exceeds existing production amounts per sharpening as that tool is no longer cutting the root or roughing the gear."

Also, the tool system can solve problems that some gear manufacturers have with carbide hobs used for both roughing and finishing because of their limited stock removal and their rate of breakage due to the roughing process.

The tool system can be made with any combination of the three tools, and the finishing hob can be made with or without the twist-free feature.

For more information:
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18013 Cleveland Parkway, Suite 180
Cleveland, OH 44135
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Fax: (216) 377-0787
E-mail: *lmtfette@lmtfette.com*
Internet: *www.lmtfette.com*

Zero-Max Debuts Keyless Shaft Locking Bushings

The ETP Express keyless shaft locking bushings provide fast and frequent mounting/dismounting capabilities with one radial screw.

According to the company's press release, the design saves space and provides accurate mounting without axial movement of the ETP bushing along the shaft. Designed to position and lock all types of gears, pulleys, sprockets and other components in a power transmission system, ETP Express bushings help provide runout control to reduce vibration and noise.

Zero-Max says the ETP Express design provides a tight connection between the shaft and mounted components. When tightened, the product's radial screw compresses a pressure medium within the double-walled sleeves that expands and creates a solid connection between the shaft and the mounting member. Uniform surface pressure prevents damage to surfaces and enables the use of shafts without keyways.

Providing concentricity to 0.001" T.I.R., these bushings handle torque ranges from 40–6,400 ft.-lbs. The only tool required to torque, mount and lock bushings into place is an Allen wrench.

For more information:
Zero-Max Inc.
13200 Sixth Ave. North
Plymouth, MN 55441-5509
Phone: (800) 533-1731
Internet: *www.zero-max.com*

Boston Gear Reducer Designed for Conveyors

A new Series 700 conveyor flange adapter (CFA) is specially designed for increased control and lower maintenance cost on material handling conveyors. The CFA 7000 is a direct-mount worm gear speed reducer that works with a drive-train and can simplify equipment design.

According to the company's press release, this product replaces the heavier chain drive mounted on many material handling conveyors and includes fewer moving parts.

The adapter is interchangeable with standard two- and four-bolt mounted bearings and attaches to existing side rails.

The patent is pending on this series, but numerous educational items are available.

For more information:
Boston Gear
Phone: (888) 999-9860
Internet: *www.bostongear.com*

Absolute Machine Tools Designs VMC for High Speed Mold Machining

The Super Hi-Net SHV-1000 vertical machining center from Absolute Machine Tools features Schneeberger roller-type linear ways on all axes, large diameter pretensioned ballscrews and an integral spindle for finishing.

According to the company's press release, the machine's heavy Meehanite castings ensure the machining center has the strength and vibration damping required to produce excellent surface finishes and extend cutting tool life.

The Y axis features four ways for support and accuracy. The Z axis is a ram-type head with no counterbalance for increased acceleration and smooth operation. Rapid rates are 944"/min. in all axes. The machine's 24,000 rpm HSK-63A spindle delivers 31 hp and 53 ft.-lbs. of torque for medium roughing and fine finishing. For more cutting torque, an 18,000 rpm HSK-63A spindle with 85 ft.-lbs. of torque at 2,400 rpm is also available.

For more information:
Absolute Machine Tools Inc.
7420 Industrial Parkway
Lorain, OH 44053
Phone: (440) 960-6911
Internet: *www.absolutemachine.com*

Scot Forge Installs World's Largest Hydraulic Press

The new 5,500-ton forging press installed at Scot Forge is the world's largest two-column, open die hydraulic press, according to the company's press release.

The press expands Scot Forge's ability to produce carbon and alloy forgings in diverse part configurations up to 80,000 lbs., including parts with hub projections, flanges and webbing. The press can provide heavier and more intricate forgings than previously available from materials with higher deformation

properties, including stainless, titanium, aluminum and nickel.

In addition, reverse extrusion processes are now available for the production of hollow parts with thinner walls and closed-end cylinders. Aided by new computer modeling software and the press' large forging window, Scot Forge has increased its ability to forge close-to-net-shape parts. The new software provides accurate forging simulations resulting in optimum forge process plans and precise tool design while the 14' x 15' forging window allows for the use of larger tooling.

The press joins six other open die presses, six hammers and four ring mills.

For more information:
Scot Forge
8001 Winn Rd.
Spring Grove, IL 60081
Phone: (800) 587-1000
Internet: ***www.scotforge.com***

Toyoda Machinery's Latest in Grinding and Horizontal Machining

Toyoda Machinery's grinder and its horizontal machining center will be on display at the company's booth at Westec Expo & Conference, held March 27–30 in Los Angeles (see events coverage on page 59 for details).

The SelectG is a universal grinder designed for flexible, precise and small-lot work. The wheelhead rotates from 90° to 60° to accommodate a straight or angle wheel. According to the company's press release, this rotation simplifies changeover from straight to angle grinding wheel. Single machine capabilities are expanded without the necessity of a full CNC-controlled wheelhead or second dedicated grinder.

The FH-S horizontal machining center increases throughput by pairing high spindle speeds with faster, non-cutting operations. According to Toyoda's press release, this accelerates cycle times by about 30%. Its modular design allows flexible configurations in various manufacturing environments. The FH-S high gain spindle can reach full speed in 2.3 seconds and is designed for quick acceleration and deceleration.

For more information:
Toyoda Machinery USA
316 University Dr.
Arlington Heights, IL 60004
Phone: (847) 253-0340

Mitsubishi EDM Technology To Be Featured at Westec

Among the assortment of products and machinery displayed at Mitsubishi's booth at the Westec show is the MD+PRO wire machine from Mitsubishi EDM, which includes a full servo B-axis indexing option to introduce two new EDM processes: 1) indexing and 2) turning and burning.

According to the company's press release, the FA-S Series incorporates key features from other product lines. The V machine's V500 ultra high speed power supply combined with its fine finish power supply and non-isolated workpiece table provide considerable speed and surface finish. A PM4 control works with the inverter-driven flushing system, providing 20–30% faster cutting speeds in poor flush conditions.

Finally, Roku-Roku's HC-658 high speed vertical machining center combines high speed machining of mold steels and a multi-purpose design that provides improved graphite-machining capability.

"We have transitioned along with the EDM industry from the days of thriving tool and die shops into more demanding and highly specialized part production markets of today," says vice president Nicolas Giannotte. "Only EDM technology can achieve the precision and accuracies demanded by markets such as medical, aerospace and power generation."

For more information:
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Gear Manufacturers Find Advantage in Indian and Asian Partners

Joseph L. Hazelton, Associate Editor

In 2003, Mini Gears faced the prospect of losing 40 percent of its business to China. Major customers wanted product from the U.K. company at substantially lower prices and were looking at going direct to China to get them. Mini Gears, however, was able to retain all of that business and has since increased its sales more than 46 percent, says Paul Darwent, the company's managing director.

The difference was Mini Gears' purchasing office in Shanghai, China. Opened just a year earlier, the office provided Mini Gears with a way to turn would-be competitors into beneficial partners.

Likewise, many U.S. and European gear manufacturers may be able to take advantage of lower-cost products from Indian, Chinese and other Pacific Rim companies by partnering with them.

Besides Mini Gears, Schafer Gear Works Inc. and Precipart Corp. have benefited from their own overseas partnerships. Located in Indiana, Schafer Gear is able to obtain lower-priced forgings from its Indian partner, JayPee Forge Ltd.

Meanwhile, Precipart is able to get business that wouldn't have been cost effective without a lower-cost, high-quality alternative provided by its GEM Network partners. "We have some large opportunities," says John P. Walter, Precipart's president & CEO.

The GEM Network is a group of companies, all ISO 9001:2002-registered, that manufactures gears, gearboxes, turned parts and mechanical assemblies and systems. The group includes European and Asian companies with operations in France, Germany, Switzerland and the United Kingdom, as well as China, Malaysia, Singapore and Vietnam. The members created the network to offer what Precipart describes as "a seamless and controlled approach to global sourcing of precision, customized products."

However, deciding whether to partner with Indian or Asian companies, finding suitable companies as partners and coordinating work with them is complicated, time-consuming and involves many questions, a main one being: How can a U.S. or European gear manufacturer make best use of an Indian or Asian partner?

For Mini Gears and Schafer Gear, best use of their Chinese and Indian partners involved having them manufacture high-volume parts. Likewise, Precipart has involved its overseas partners in high-volume manufacturing.

High-Volume Production

Higher volumes take greater advantage of the partners' lower material and production costs. For example, Walter cites lower-cost gear blanks as helping Precipart compete in the market for high-volume gears.

Precipart manufactures fine-pitch, high-precision gears for specialty markets. Its gear types include spur, helical, bevel, worm and internal ring gears, as well as worm wheels. Located in Farmingdale, NY, the company also manufactures gearboxes and gear assemblies.

"We stay away from standard, off-the-shelf items," Walter says. "We're a custom house."

Custom houses can be approached about high-volume manufacture, though. For instance, Precipart was engaged in the production of shafts with helical gear teeth. However, it had an opportunity for high-volume production.

Precipart was already receiving the shafts from an Asian partner, but Precipart thought its partner could cut the shafts' gear teeth, too. However, the GEM Network partner wasn't a gear manufacturer. So it flew one of its engineers to New York for training at Precipart's Farmingdale facility. During a monthlong stay, the engineer was educated in the manufacture of gears. Also, his company purchased the necessary gear-cutting machinery to start production. "They're off and running, producing a quality product," Walter says.

Having partners in China means traveling there a number of times a year for Mini Gears' managing director, Paul Darwent (third from left). Besides Darwent, other company officers and technical staff sometimes have to fly to China to work with their suppliers. Also in the picture are Mini Gears' chairman, Reg Darwent (fifth from left), and its operations director, Phil Darwent (sixth from left).

Likewise, Mini Gears was manufacturing high volumes of geared shafts in its factory, located in Stockport, England. The shafts were valve gear shafts of various sizes, and the volumes were 2,000–3,000 of each size per month. That production was outsourced to a Chinese company via Mini Gears' Shanghai purchasing office.

The advantage from higher volumes can be even greater when the manufacturing orders come from longer-term contracts. These recurring orders allow U.S. and European companies to qualify a product from their overseas partners and not have to requalify it because the product doesn't change from order to order.

Schafer Gears' partnership with JayPee is an example, even though it doesn't buy gears from JayPee. Schafer Gear itself manufactures spur, helical, bevel and worm gears, as well as gear shafts, for various uses, including industrial, agricultural, automotive and off-highway applications. Located in South Bend, IN, the company obtains machined forgings for customers with whom it has multi-year contracts for higher-volume production. It doesn't use JayPee for short-term contracts or for low-volume production.

Bipin N. Doshi, Schafer Gear's president, explains that it takes time to establish product quality and arrange the logistics of an order. "If every job is different, the technical interaction has to be strong," Doshi says. He adds that: "The reaction time for any engineering changes is longer, and overseas partners cannot react as fast as we can in emergency situations."

However, U.S. and European gear manufacturers can't decide to transfer their high-volume jobs to countries like China and India just because they see cost savings. For instance, a manufacturer may find a Chinese company able to make a lower-cost gear that meets quality and performance criteria. But the lower cost has to create savings big enough to be an advantage to the U.S. or European company and its customer and big enough to survive the additional costs of foreign manufacture, one obvious cost being shipment from overseas.

"The right combination has to occur for an advantage," Doshi says.

Greater Capacity or Capabilities

Besides cost savings, another advantage of partnering with an Indian or Asian company is increased capacity or capabilities without more capital investment.

For example, Schafer Gear added capacity though its other Indian partner, Hi-Tech Gears Ltd. Schafer Gear and Hi-Tech formed their partnership in 2004, when Schafer Gear was trying to win business from a potential customer. Schafer Gear was working with the customer to improve the reliability of one of its gear products, but the customer also wanted to reduce the product's cost. Schafer Gear could lower the cost by having Hi-Tech manufacture the product. By partnering with Hi-Tech, Schafer Gear bolstered its chances of winning the customer's business, but it also gained the capacity of a high-volume manufacturer of automotive gears. This added capacity came without Doshi having to buy any more machines for his factories in South Bend, IN, and Rockford, IL.

Similarly, Precipart extended its capabilities via its GEM Network partners. For example, through these partners, Precipart can supply customers with ground spiral bevel gears and large diameter gears, among many other types, in low to medium volumes even though it may not have these capabilities itself.

"We have additional resources we can draw on that we don't specifically have in-house, without compromising product quality" says Don Weinzimer, Precipart's vice president of special programs. Moreover, Precipart partnered with companies whose capabilities

CORRECTION

Gear Technology's November/December 2005 issue contains a mistake in the article "Gear Expo: Still a Tool for Business." The article, which appears on pages 46–47, includes a sentence that refers back to IMTS 2004 as follows: "Another exhibitor there was Gleason Corp., whose vice president–American sales, Mark Hiscock, ..."

The sentence should have read: "Another exhibitor there was Gleason Corp., whose then-vice president–American sales, Mark Hiscock, ..."

We apologize for the error. Gleason's vice president–American sales is John M. Terranova.

—The Editors

went beyond gear manufacturing.

The advantages of lower-priced products and more capacity or capabilities, however, have to be weighed against the disadvantages of partnering with Indian and Asian companies.

The Time to Qualify Product

Mini Gears' Darwent says the biggest disadvantage is the time needed to outsource a new gear job with a new gear manufacturer. The U.K. company has more than 12 suppliers in China and does business with 6 or 7 of them on a monthly basis. These suppliers can complete a gear job in six weeks when it's within their capabilities. When it isn't, Mini Gears has to look for a new supplier.

In that case, the company needs about six months to find and contract with a new Chinese gear manufacturer. "It means our staff in China has to start from the beginning," Darwent says. And finding a qualified gear manufacturer means paperwork, including pricing information and quality plans from the supplier. "There's just a whole list of things we've got to go through," Darwent says.

Moreover, six months is only the *usual* amount of time. "It can go up to 9 months," Darwent says.

Communicating with Overseas Partners

Another disadvantage with partners in India and Pacific Rim countries like China and South Korea is the time difference. For example, when Doshi reaches Schafer Gear at 8 a.m. on a Monday, it's 6:30 p.m. that day in Mumbai (formerly Bombay). JayPee is already closed for the day.

Doshi can e-mail and have an answer Tuesday morning, but he can't have the immediate give-and-take of a live conversation unless he's at his office at odd hours, such as 9:30 p.m., which is 8 a.m. the next day in Mumbai. Then Doshi can phone JayPee.

Inventory Management

Doshi points out another disadvantage: inventory management.

India is far away, so JayPee can't provide immediate delivery of gear blanks, even of ones it's made many times before. Also, flying gear blanks to the U.S. is expensive. So Schafer Gear has to maintain in the U.S. its own inventory of JayPee gear blanks.

"There's a lot more money tied up in inventory," Doshi says. "That goes into the cost-price question."

Advantages May Disappear

U.S. and European gear manufacturers need to understand that an advantage they have today may be gone tomorrow. That's what happened to Schafer Gear while partnered with Hi-Tech in an effort to win business from a potential customer. Schafer Gear's cost savings for the job came from India's lower price for steel. But steel prices went up, Doshi says, and they rose faster in India than in the U.S. Schafer Gear's cost advantage disappeared, and the company didn't win the job.

However, Schafer Gear's partnership with Hi-Tech didn't end. "They're OK with waiting for the right combination," Doshi says.

Also, weighing advantages and disadvantages of partnering with Indian and Asian companies isn't the end of a U.S. or European gear manufacturer's work. If partnering is still a good idea, the manufacturer next needs to find partners, make arrangements to facilitate the partnerships and then maintain its relationships with the partners.

Finding Partners

Focused on China, Darwent investigated its gear manufacturing capabilities. He arranged to visit more than a dozen Chinese gear manufacturing companies willing to work with U.S. and European businesses. During his visit, the Mini Gears' managing director noticed three main things about the companies: 1.) there were as many good companies as there were bad, 2.) there was some automating of manufacture, but 3.) the companies were mainly using mechanical machines to manufacture gears, from turning to gear grinding.

Darwent decided China had a large skill base in gear manufacturing and found their use of mechanical machines to be telling. "Ironically, you need more skill to do that," he says.

Besides finding suitable partners, Darwent had to concern himself with creating a Mini Gears operation in China, specifically a purchasing office. That way, he could have a local employee working directly with Mini Gears' suppliers. However, that agent had to meet certain requirements.

A Middleman for Mini Gears

To be most useful, the middleman had to be fluent in Chinese and English and had to be an engineer. Also, he'd need to have experience sourcing manufacturers.

The search might've taken some time, but Darwent lucked out. He met his future employee at a dinner during his first trip to China. The dinner was hosted by a Chinese company Darwent was visiting. The company was having the dinner for several visiting customers.

During the meal, Darwent happened to meet a university-trained engineer who had been working for a large sourcing company for several years. The engineer spoke Chinese and English. Also, Darwent could get a report on the engineer's competence. His sourcing company's clients included one of Mini Gears' main customers.

"They knew him very well and spoke of him very highly," Darwent says. Still, he went through a formal interview in the U.K. with Jason Chen, who now heads Mini Gears' Shanghai office.

Opening an Overseas Office

To open the office, Mini Gears had to work with the Chinese government, specifically Shanghai's regional government.

"You need special clearance in China to open up what's called a representative office, which is what Mini Gears has," Darwent says. "There's a lot of paperwork involved." For example, Darwent had to provide the regional government with certified copies of Mini Gears accounts from the previous three years to show that it was a financially stable company.

Precipart partnered with six other companies to form the GEM Network, allowing Precipart to extend its production capabilities beyond gear manufacturing. The above parts include sector gears made by Precipart and a number of Swiss turned parts made via the GEM Network.

Darwent says he was surprised at how much information the government asked for, but he guessed the government asked for so much because it didn't want to permit small agents to enter the business community, buy product, then disappear after a few months without paying their bills. "The authorities are looking for professional companies who are investing for the long term."

Working with the Government

Meeting the government's requirements and getting its approval took about six months. But Darwent wasn't unhappy about the amount of time. He says he's heard of companies having to wait 12–18 months to open their own operations in China.

Also, Darwent and Chen were busy visiting gear manufacturing companies to review them as potential suppliers. Naturally, this required Darwent to fly back and forth to China. "The six months passed very quickly," Darwent says.

After receiving approval, Mini Gears had less paperwork to file with the government to meet continuing legal requirements. "The paperwork isn't too bad," Darwent says.

The company files paperwork with the government at the end of each year, including an abbreviated set of accounts of business done or in progress in China. Also, it has to pay taxes for its office employees and withhold money from their paychecks to pay their income taxes. But, Mini Gears pays the office bills from the U.K.

In contrast, Precipart and Schafer Gear didn't open their own operations, so they don't have to deal with any Indian and Asian governments. They work with their Indian and Pacific Rim partners, who deal with the governments themselves.

Working with Overseas Operations

Gear manufacturers have to devote time to their overseas partners, but the amount of time can vary. For example, Mini Gears spends a lot of time working with its Chinese partners. That means a number of flights to China for company officers and technical staff. "You do need lots of visits," Darwent says.

Schafer Gear doesn't visit its forgings partner much, though. Doshi visits JayPee about once a year, but his trips aren't about the Indian company. Doshi returns to his homeland from time to time and uses the trips as occasions to stop by JayPee. "I don't make a specific trip for business," he says.

However, his visits are so intermittent because he has no problems with JayPee's products. If there were issues, Doshi says, he'd likely have to visit more often. As for visiting Hi-Tech: "Until we have a customer, we don't need to go there."

Precipart meets with its GEM Network partners on an ongoing basis, with meetings at least twice a year, including a main annual meeting in October and a secondary one at another time. These gatherings are in addition to regular communication via e-mail, teleconferences and video conferences.

For Precipart, its overseas partnerships have meant more orders. Likewise, overseas partnerships have helped Mini Gears' business, allowing it to change its U.K. factory. With its high-volume work done in China, Mini Gears can focus its factory on more specialized, small- to medium-volume gear jobs. It can also concentrate on its specialty, gear rack manufacturing.

In 2003, Mini Gears manufactured 750,000 feet of gear racks. In 2005, it had orders for more than 1.25 million feet. Darwent says Mini Gears has bought three new machines for manufacturing gear racks in the last 12 months, so the company now has seven machines dedicated to cutting gear racks 24 hours a day.

Schafer Gear Works uses Indian partner JayPee Forge to obtain lower-priced forgings, then performs the gear-manufacturing operations itself.

"We intend to keep that completely in the U.K.," he adds.

Moreover, Mini Gears has used some of its China profits to upgrade its U.K. factory, including purchase of a large milling center with a three-meter capacity.

Schafer Gear's partnership with JayPee has worked out well, too. The South Bend company has been able to obtain lower-priced forgings without sacrificing quality. "Zero quality defect," Doshi says. "They have been very good on quality."

The partnership with Hi-Tech hasn't worked out as hoped. Schafer Gear hasn't made money from it, but it hasn't lost any, either. And if the right order comes along, Schafer Gear has a qualified supplier standing by. "We feel that once we get the right opportunity," Doshi says, "we'll get approval pretty fast."

However, Doshi points out a must-have from all overseas partners: "If the quality lacks, then the other advantages aren't worthwhile."

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GEAR MANUFACTURING IN THE FAR EAST

Profiles and insight from gear manufacturers on the other side of the world

William R. Stott, Managing Editor

Photos courtesy of Elecon Engineering Co. Ltd.

Introduction

This article proposes to give readers a glimpse of some companies that manufacture gears in the Far East. We've talked with more than a dozen companies in India, Taiwan and Korea—companies ranging in size from as small as 30 employees to more than 11,000 and serving a variety of industries, including fine-pitch gears, automotive gears and large industrial gears. We talked to both gear job shops and captive operations.

For your convenience, a complete list of the companies we interviewed is available at the end of this article, along with some additional sources of information on gear manufacturing in these countries.

This is not intended to be a scientific survey, and it shouldn't be taken as such. It's just a glimpse, and hopefully it will give those of you who are curious a better feel for what's happening in gear manufacturing on the other side of the world.

Rapid Growth

Virtually every company we interviewed is experiencing substantial—and in some cases, phenomenal—sales growth.

Shang Yang Industrial Co. Ltd. is a Taiwanese manufacturer of AC motors and gearmotors as well as a line of coin hoppers designed for use in slot machines and other casino games. The company employs 50 people.

"We have grown a lot this year and last year," says overseas sales manager Chen Tai Hui. "That's why we're preparing to move to a new factory." The company currently occupies a 2100-square-meter factory, but will be doubling its space in 2006, Chen says.

Shang Yang only recently began manufacturing gears, Chen says, because the quality of gears it had been buying from an outside supplier was not good enough. "So we decided to make the gears ourselves to suit our motors and gearboxes. We think the primary reason for our company's growth has been manufacturing gears to suit our product."

Chen expects modest growth for 2006 of about 5%.

Dae Seong Gear Manufacturing Co. of Inchon, Korea, has also grown substantially over the past five years. Dae-Sung Jung, managing director, says the company's sales have grown by about 35% over the past five years, and he expects additional growth of about 10% in 2006. Dae Seong manufactures large-diameter spur, helical, straight bevel and spiral bevel gears primarily for heavy industries such as cement, steel and iron processing. Its growth has been mainly from increased demand in those industries, he says.

One company that has seen only marginal growth is Precision Engineering and Chiming Equipments, located in Bangalore, India. Over the past five years, the company has grown only marginally, says proprietor B.V. Swaminathan, and he expects growth of about 8-10% in 2006.

Precision Engineering & Chiming manufactures mainly fine-pitch gears for electric meters, servo motors and automotive speedometers, wiper motors and window lifts. One of the challenges Swaminathan's company has faced is that the metal gears he manufactures are becoming obsolete in the applications he's traditionally served. "We do not feel much change, as most of our items get replaced by plastic gears."

Still, Precision Engineering & Chiming has managed growth by staying ahead of the capabilities of plastic gears, "getting into newer fields like from clock to telephone, from telephone to dot matrix printer, from printer to washing machine and so on," Swaminathan says.

Most of the rest of the Indian companies we interviewed have experienced tremendous growth over the past five years.

"In terms of annual sales, our business has multiplied many times over the last five years," says Arvinder Singh, managing director of Punjab Bevel Gears Ltd. "We hope to double annual sales in the year 2006."

Punjab Bevel Gears employs 213 people and occupies more than 170,000 square feet of factory space, 65,000 square feet of which is dedicated to gear manufacturing equipment.

Singh attributes his company's phenomenal growth to "the excellent quality of products and competitive prices, supplemented by a well-qualified and experienced marketing and technical backup."

Many Indian manufacturers have been boosted by the steady growth of the Indian automotive industry. Punjab Bevel Gears manufactures differential gears, transmission gears and transmission shafts for agricultural tractors, trucks, pick-ups and passenger cars.

According to the Automotive Component Manufacturers Association of India (ACMA), the Indian automotive component industry grew by about 30% in 2005, and the organization expects this growth to continue.

"The last three years have been good, and going by the prevailing trends, I am confident that this high growth shall continue for the next three years also," wrote Deep Kapuria, past president of ACMA in the organization's 2004-5 annual report. Kapuria is also chairman and managing director of Hi-Tech Gears.

Ashok Leyland is a manufacturer of buses and trucks with more than 11,000 employees and gear manufacturing operations covering more than 62,000 square meters of factory space in six locations in India, according to Rajinder Malhan, executive director–business development.

Ashok Leyland has seen year-over-year growth of about 30% over each of the last five years, and the company expects an additional 20% growth in 2006, Malhan says.

The biggest gear manufacturing challenge facing the company is capacity constraint, Malhan says. Ashok Leyland is looking to expand its gear manufacturing capacity by at least 50%.

In addition to those serving the automotive industry, many of the traditional gear manufacturing industries also appear to be booming in India, according to the companies interviewed for this article.

The Jamal Group of Companies specializes in bevel gears, ranging from 5 mm to 850 mm in diameter. Although it is a supplier of automotive differentials, it also serves a wide variety of industries including machine tools, railway equipment, cooling towers, heavy industry, power tools, boats and radio-controlled cars and airplanes, among others.

Sulaiman Jamal, managing director, says the company has grown by more than 50% over the past five years, and he expects 30% growth in 2006. Jamal says much of his company's growth has been due to the introduction of new product lines and his company's use of increasingly higher levels of technology.

Trina Engineering, INGECO Gears Pvt. Ltd. and Universal Gear Industries & Engineering Works all manufacture gears for heavy industry. Each company has grown substantially over the last five years.

Elecon Engineering Co. Ltd., one of the largest manufacturers of industrial gears in India, has been growing at an annual rate of about 30% per year for the past five years, and the company expects to grow by another 25% in 2006, says B.I. Patel, chairman and managing director. Elecon's gear division employs 318 people and has more than 23,000 square meters of factory space devoted to gear manufacturing equipment.

The company's growth has been due to increased demand from steel, cement, sugar and material handling industries, as well as orders from the Indian navy, Patel says. Also, the company has expanded its manufacturing facilities and found new applications for its products.

Exponential Growth in Exports

Exports are driving much of the growth being experienced by the companies interviewed for this article.

At Kyung-In Gear of Inchon, Korea, export growth has been gradual. The company supplies large-diameter gears for the steel, shipbuilding and cement manufacturing industries. "We mainly have business relationships with Japan and other Asian countries," says Ju-Kyung Kim, CEO. The company sees America as the biggest potential market. Until now, the company has not been prepared to enter it, but he adds: "We are aiming to challenge the worldwide market such as North America and Europe."

While export growth has been gradual at a few of the companies we talked to, at others, it's transforming their businesses.

For example, Shang Yang Industrial Co. didn't export at all five years ago, but today, exports to other countries in Southeast Asia account for 70% of the company's business, says Chen. He sees additional export opportunity in China, Russia, Brazil and India.

Five years ago, exports accounted for about 10% of the annual sales at Punjab Bevel Gears. Today, they account for about 50%, says Singh. Punjab Bevel Gears' products are exported to countries around the world, including North America (USA & Mexico), South America (Chile & Argentina), Europe (UK, France, Germany, Italy & Turkey), Africa and the Far East.

Singh mentions the United States, Europe, Africa and Iran as all having large export potential for his company.

Trina Engineering didn't export at all five years ago, according to director of marketing Pankaj Khera, but today, exports to the United States, Canada, the United Kingdom and other countries amount to 60% of the company's business.

Most of the others tell similar stories. INGECO exported 15% of its business five years ago. Today, the company exports 45%. Over the same period, Dae Seong went from 5% exports to 20%. Precision Engineering & Chiming went from 10% to 40%. Elecon went from 5% to 15%. The Jamal Group went from no exports to 40%.

Clearly, it's becoming a much smaller world—and the pace is quickening.

Some of these companies have their eyes on the United States and European markets, but nearly all of them mentioned Africa, Russia, the Middle East and the Far East as having significant export potential.

Challenges

The primary challenges facing most of these companies are meeting demand and improving technology. Many of them are growing so fast that they can't keep up with the demand. Also, while most of the companies we talked to are buying quality used machinery to improve their technology, there are some notable exceptions, and you also get the sense that these companies are more likely to be new machinery buyers in the near future.

Shang Yang Industrial Co., for example, bought a new CNC gear measurement system in 2005 to help analyze gear noise, says Chen.

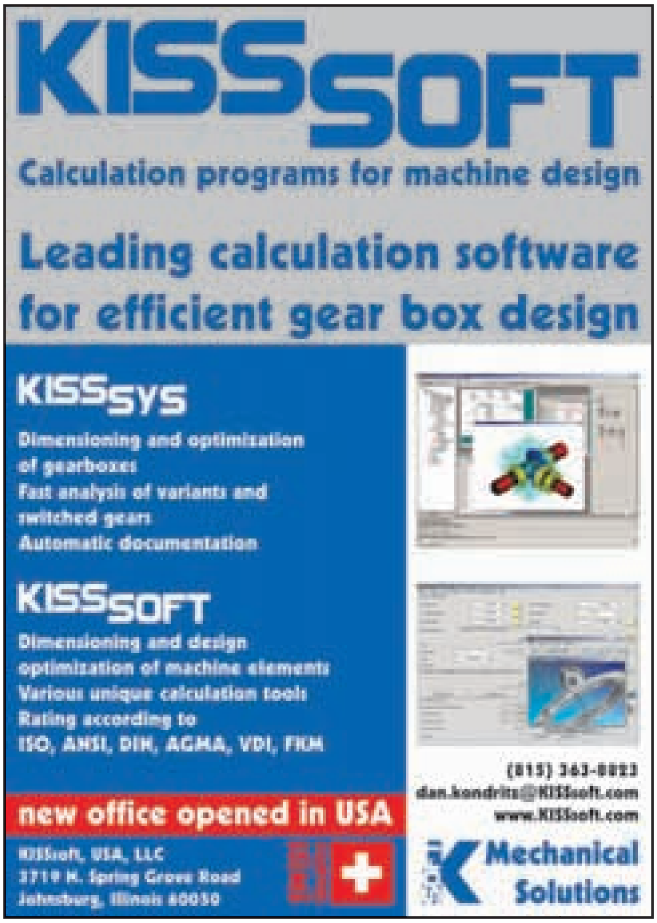
Dae-Sung Jung of Dae Seong Gear says that his company has invested in a new spiral bevel gear cutting machine and a new large-diameter profile grinder in 2005.

His counterpart, Ju Kyung Kim, at Kyung-In Gear admits that most Korean gear manufacturers are still using older technology. But that has begun to change over the past 15–20 years, he says. Kyung-In Gear has invested in newer equipment, and the company plans to install a new Gleason-Pfauter P5000G as part of a factory expansion next year.

In 2005 Trina Engineering invested in a number of machine tools. "Of course, these were good, pre-owned machines," says Khera, but he adds that next year, the company is considering a new CNC gear grinder.

Regardless of the type of machine tools purchased, nearly all the companies are concerned with improving productivity and quality. A number of them have instituted or begun instituting modern manufacturing concepts.

"We are continuously improving the quality of the product, as well as going towards the Six Sigma concept," says Patel of Elecon Engineering. He adds that "We are trying to pursue the concept of just-in-time to reduce inventory and reduce pressure on our suppliers."



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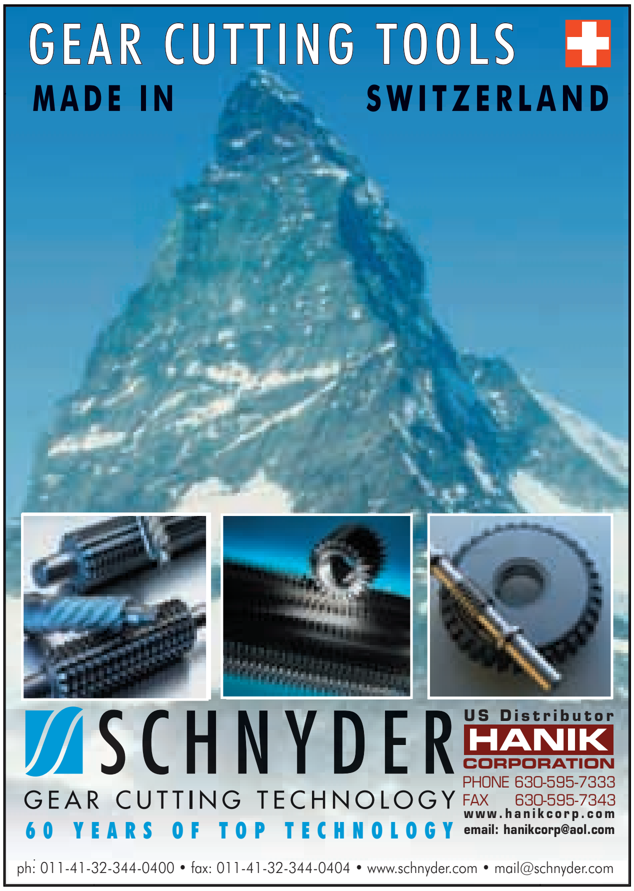
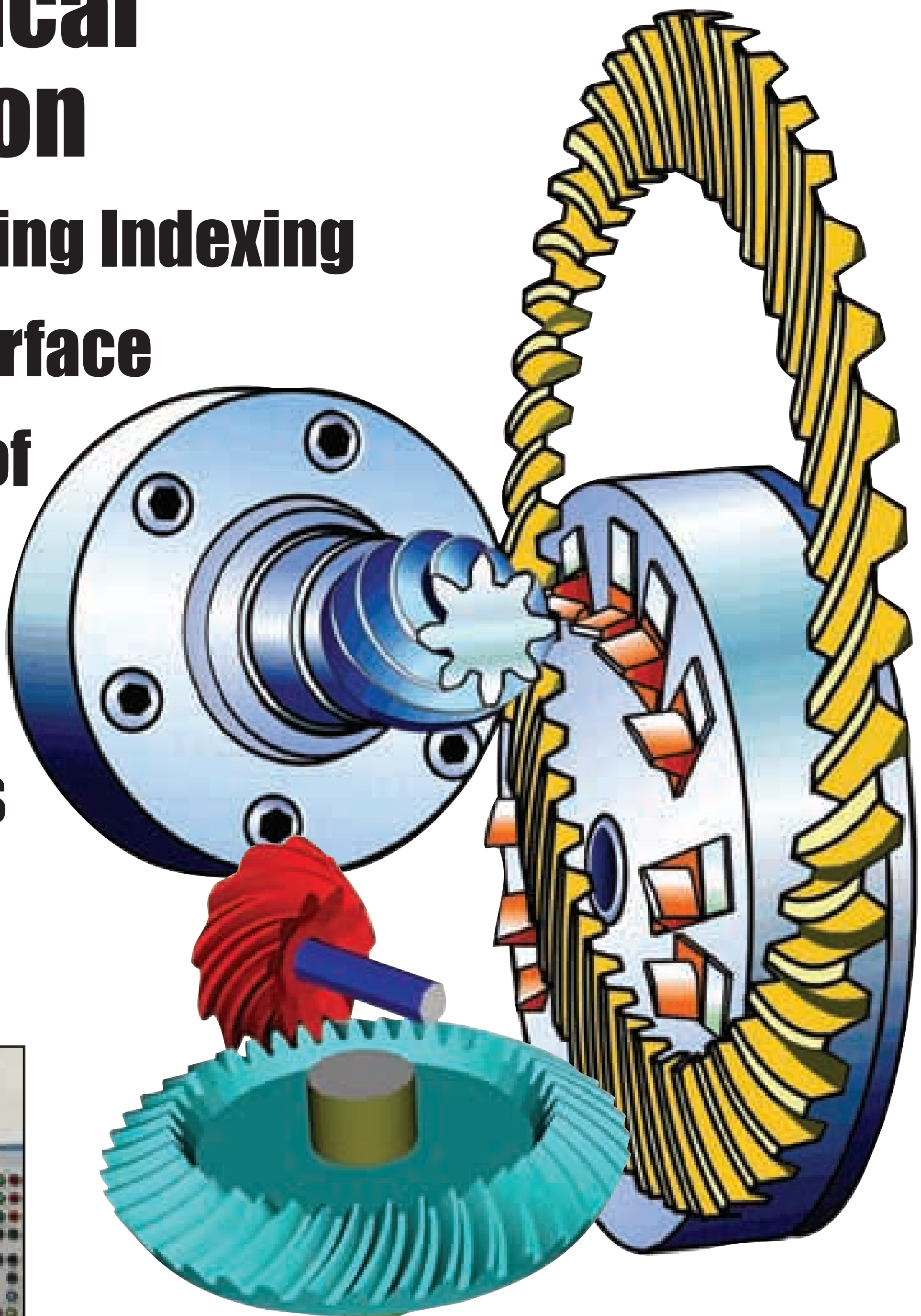


Kinematical Simulation

of Face Hobbing Indexing and Tooth Surface Generation of Spiral Bevel and Hypoid Gears

Dr. Qi Fan



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Management Summary

In addition to the face milling system, the face hobbing process has been developed and widely employed by the gear industry for manufacturing spiral bevel and hypoid gears. However, the mechanism of the face hobbing process is not well known by gear researchers and engineers. This paper presents the generalized theory of the face hobbing process, mathematical models of tooth lengthwise curve generation and tooth surface generation. The face hobbing indexing motion is simulated and visualized. A face hobbing tooth surface generation model is developed, which is directly related to the kinematical mechanisms of a physical bevel gear generator. The developed mathematical models accommodate two categories of the face hobbing system: non-generating (Formate) and generating.

Introduction

There are two types of face hobbing processes used to generate the tooth surfaces of spiral bevel and hypoid gears, a non-generated (Formate®) process and a generated process (Refs. 1, 2, 3). However, the pinion is always manufactured using a generated process.

The major differences between the face milling process and the face hobbing process are: (1) in the face hobbing process, a timed continuous indexing is provided, while in the face milling process, the indexing is intermittently provided after cutting each tooth side or slot. Similar to the face milling process, in the face hobbing process, the pinion is cut with a generated method and the gear can be cut with either a non-generated (Formate®) or a generated method. The Formate method offers higher productivity than the generating method because generating roll is not applied in the Formate method. However, the generating method offers more freedom for controlling tooth surface geometries; (2) the lengthwise tooth curve of face milled bevel gears is a circular arc, while that of face hobbed gears is an extended epicycloid; and (3) face hobbing gear designs use a uniform tooth depth system, while face milling gear designs use a tapered tooth depth system.

Theoretically, the face hobbing process is based on the generalized concept of bevel gear generation in which the mating gear and the pinion can be considered respectively generated by the complementary generating crown gears, as shown in Figure 1. The tooth surfaces of the generating crown gear are kinematically formed by the traces of the cutting edges of the tool blades, as shown in Figure 2. The generating crown gear can be considered as a special case of a bevel gear with 90° pitch angle. Therefore, a generic term "generating gear" is usually used. The concept of a complementary generating crown gear is considered when the generated mating tooth surfaces of the pinion and the gear are conjugate. In practice, in order to introduce mismatch and crowning of the mating tooth surfaces, generating gears for the pinion and the gear may not be complementarily identical. The rotation of the generating gear is represented by the rotation of the cradle on a hypoid gear generator.

The face hobbing system can use advanced design methodology to formulate the parameters of the generating gears. As a

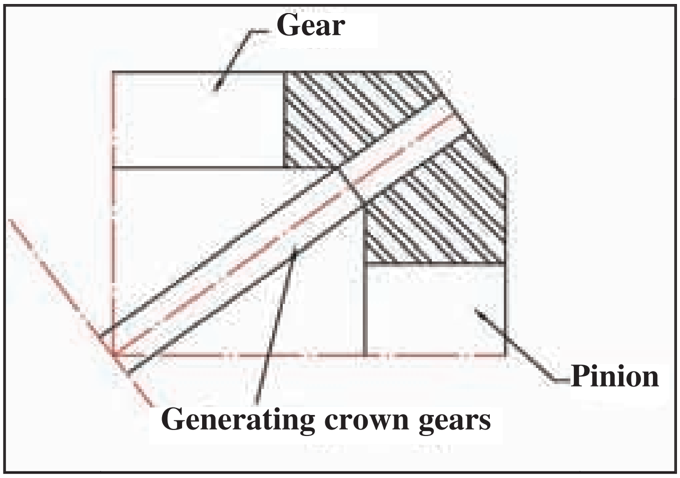


Figure 1—Basic concept of bevel gear generation.

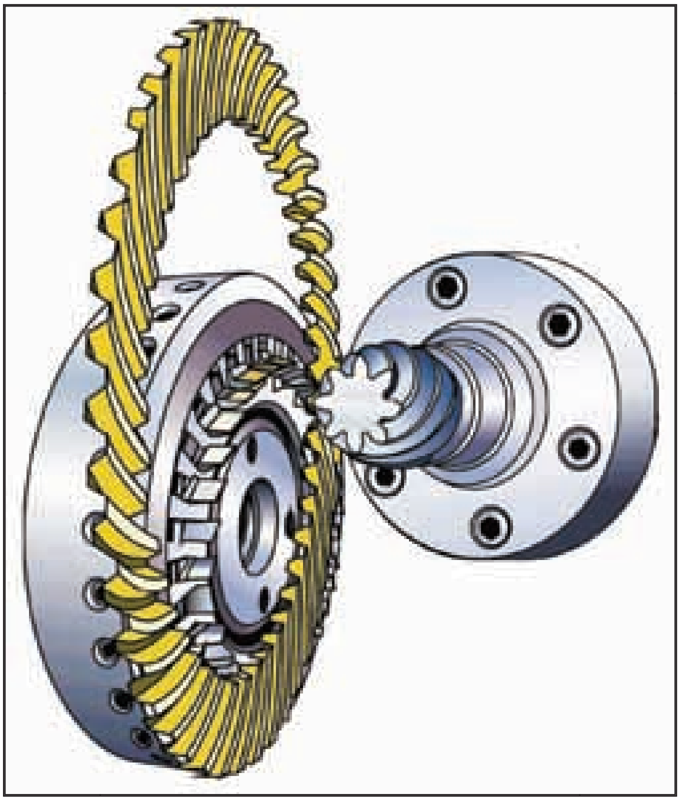


Figure 2—Relationship of the cutting tool, generating gear and the work.

result, face hobbed spiral bevel and hypoid gear sets can offer optimized bearing contact, bias direction and function of transmission errors, resulting in reduced working stresses, vibration and noise. Optimized face hobbed gear sets are less sensitive to errors of alignment.

Related Motions of the Face Hobbing Process

In the generated face hobbing method, two sets of related motions are defined. The first set of related motions is the rotation of the tool (cutter head) and the rotation of the work (workpiece), namely,

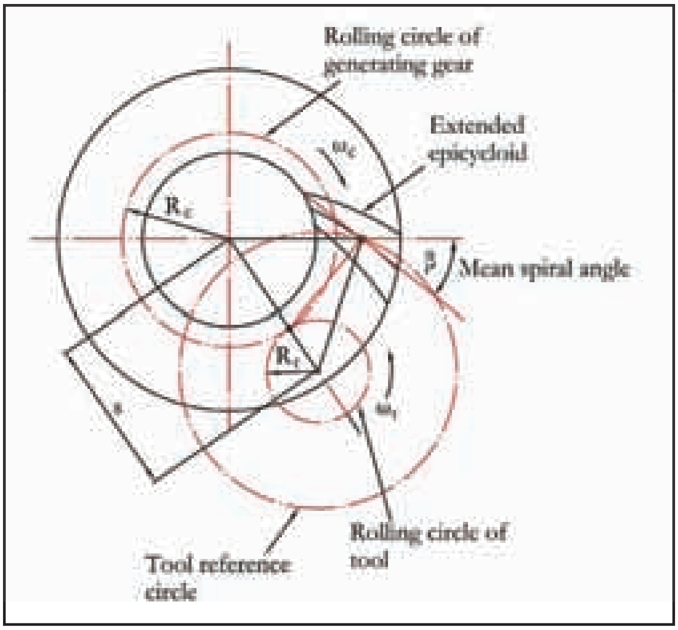


Figure 3—Generation of extended epicycloids.

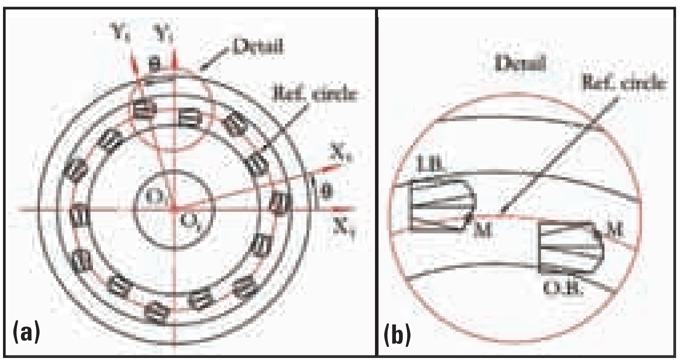


Figure 4—Face hobbing cutter head and blades.

$$\frac{\omega_w}{\omega_t} = \frac{N_t}{N_w} = R_{tw} \qquad (1)$$

Here, ω_t and ω_w denote the angular velocity of the tool and the work; N_t and N_w denote the number of blade groups and the number of teeth in the work, respectively. This related motion provides indexing between the tool and the work. The indexing relationship can also be represented by the rotation of the tool and the generating gear as,

$$\frac{\omega_c}{\omega_t} = \frac{N_t}{N_c} = R_{tc} \qquad (2)$$

where ω_c and N_c denote the angular velocity of the generating gear and the tooth number of the generating gear, respectively. Meanwhile, the indexing motion between the tool and the generating gear kinematically forms the tooth surface of the generating gear with an extended epicycloid lengthwise tooth curve, as shown in Figure 3. The radii of the rolling circles of the generating gear and the tool are determined respectively by

$$R_c = \frac{N_c}{N_t + N_c} \cdot s \qquad (3)$$

and

$$R_t = \frac{N_t}{N_t + N_c} \cdot s \qquad (4)$$

here s is the machine radial setting.

The second set of related motions is the rotation of the generating gear and rotation of the work. Such a related motion is called rolling or generating motion and is represented as

$$\frac{\omega_w}{\omega_c} = \frac{N_c}{N_w} = R_a \qquad (5)$$

where R_a is called the ratio of roll. Basically, the second set of related motions provides generated tooth geometry in the profile direction.

In the non-generating (Formate®) face hobbing process, only the first set of motion or indexing motion is provided for the gear tooth surface generation. Therefore, the gear tooth surfaces are actually the complementary copy of the generating tooth surfaces.

Tool Geometry

The Gleason face hobbing process uses TRI-AC® or PENTAC® face hobbing cutters. Face hobbing cutters are different from face milling cutters. The cutter heads accommodate blades in groups. Normally, each group of blades consists of an inside finishing blade and an outside finishing blade with reference point M located at a common reference circle, and the blades are evenly spaced on the cutter head (see Fig. 4). In some specially designed cutter heads, the inside and outside blades are not evenly spaced and therefore the blade radial position is correspondingly adjusted. Basically, the tool geometry can be defined by the major parameters of the blades and their installation on the cutter heads. Since the face hobbing tooth surfaces are kinematically generated by the cutting edges of the blades, an exact description of the cutting edge geometry in space is very important.

The blade edge geometry can be described in the coordinate system S_t that is connected to the cutter head with rotation parameter θ. The major parameters that affect the cutting edge geometry are: nominal blade pressure angle α, blade offset angle δ, rake angle λ, and effective hook angle κ.

Figure 5 shows a basic geometry of the inside and outside blade edges, which are represented in the coordinate system S_b that is fixed to the front face of the blade. The origin O_b coincides with reference point M at reference height h_b. Generally, the blade geometry consists of four sections: (a) tip, (b) Toprem®, (c) profile, and (d) Flankrem. Sections (a) and (d) are circular arcs with radii r_e and r_f respectively. Sections (b) and (c) can be straight lines, circular arcs, or other kinds of curves. Section (c) generates the major working part of a tooth surface. Toprem and Flankrem relieve tooth root and tip surfaces in order to avoid root profile interference and tooth tip edge contact. In order to obtain a continuous tooth surface, the four sections of the blade curves should be in tangency at connections. For a current cutting point P on the blade, the position vector and the unit tangent can be defined in the coordinate system S_b,

$$\mathbf{r}_b = \mathbf{r}_b(u) \tag{6}$$

$$\mathbf{t}_b = \mathbf{t}_b(u) \tag{7}$$

where u is the parameter.

Equations 6 and 7 can be represented in the cutter head coordinate system S_t, as

$$\mathbf{r}_t = \mathbf{M}_{tb}(\delta,\lambda,\kappa,R_b)\mathbf{r}_b(u) \tag{8}$$

$$\mathbf{t}_t = \mathbf{M}_{tb}(\delta,\lambda,\kappa,R_b)\mathbf{t}_b(u) \tag{9}$$

here matrix M_{tb} denotes the coordinate transformation from S_b to S_t. Coordinate system S_i is used to represent the rotation of the cutter head with an angular displacement θ. From Figure 4, one can obtain the transformation matrix M_{it} and represent the blade geometry in system S_i as

$$\mathbf{r}_i = \mathbf{M}_{it}(\theta)\mathbf{r}_t(u) = \mathbf{r}_i(u,\theta) \tag{10}$$

$$\mathbf{t}_i = \mathbf{M}_{it}(\theta)\mathbf{t}_t(u) = \mathbf{t}_i(u,\theta) \tag{11}$$

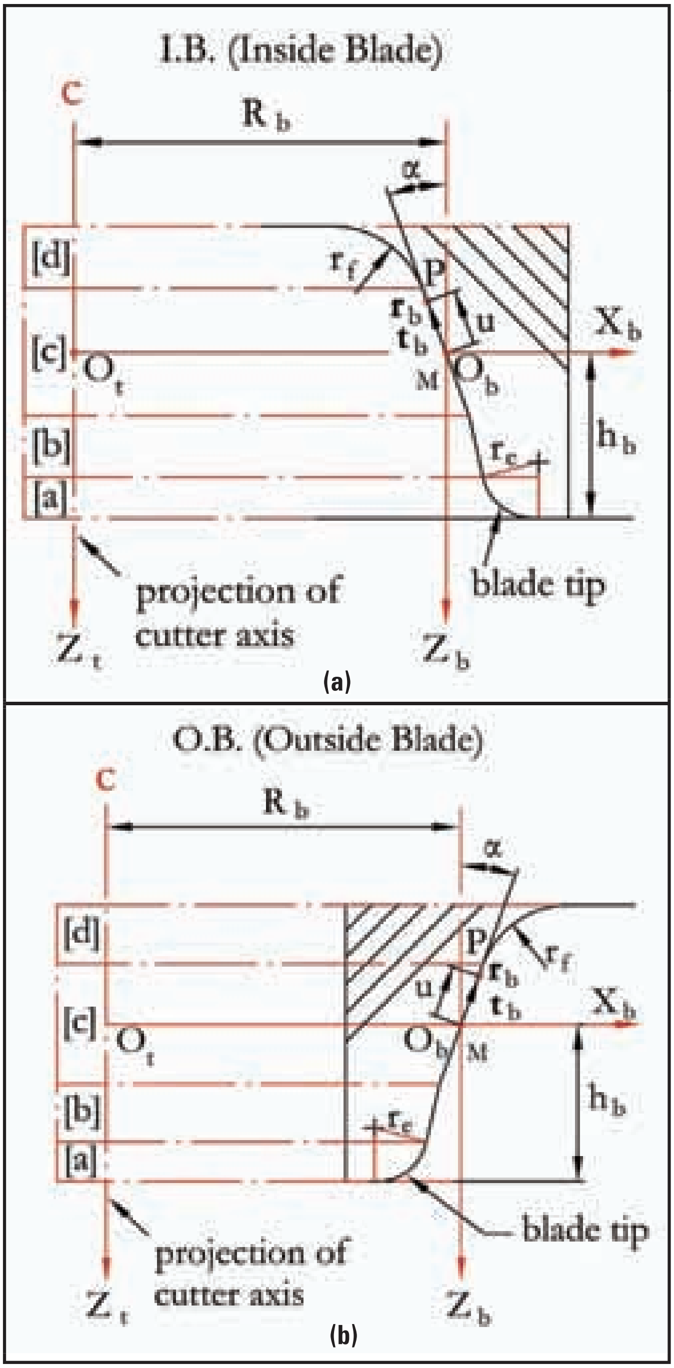


Figure 5—Blade geometry.

Kinematical Simulation of Face Hobbing Indexing Motion

As described above, the indexing motion generates the cutting path or the tooth lengthwise curves that are called the extended epicycloids (see Fig. 3). The indexing motion can be simulated and visualized in terms of the motion relationship between the generating gear and the cutter. Furthermore, such a motion can be represented in the cross-section plane that intersects the blade edges at the reference

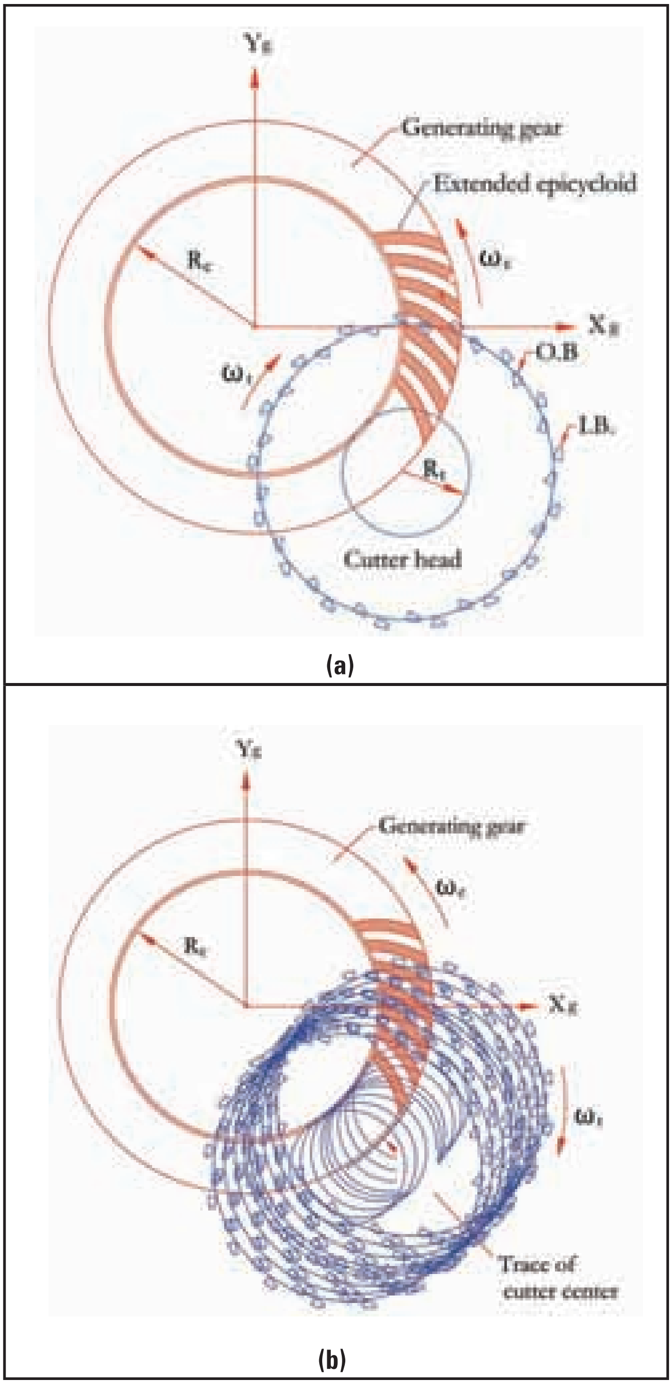


Figure 6—Simulation of face hobbing indexing motion.

$$\begin{bmatrix} x_g \\ y_g \end{bmatrix} = \begin{bmatrix} \cos[(1+R_{tc})\theta] & -\sin[(1+R_{tc})\theta] \\ \sin[(1+R_{tc})\theta] & \cos[(1+R_{tc})\theta] \end{bmatrix} \begin{bmatrix} x_t \\ y_t \end{bmatrix} + \begin{bmatrix} S_H \cos(R_{tc}\theta) + S_V \sin(R_{tc}\theta) \\ S_H \sin(R_{tc}\theta) - S_V \sin(R_{tc}\theta) \end{bmatrix}$$

Figure 7—Equation 12.

point M and is perpendicular to the axis of the generating gear so that the motion can be visualized on a plane, as shown in Figure 6. The simulation is based on the following matrix transformation, which represents the relative motion of the cutter head with respect to the generating gear.

(See Figure 7 for Equation 12)

The coordinate system S_g is connected to the generating gear (Fig. 6), and x_g and y_g are the coordinates of the tooth lengthwise curves, i.e., the extended epicycloids. Coordinates x_t and y_t specify points on the blades in system S_t. S_H and S_V are the initial horizontal and vertical settings of the cutter head. Giving a value to parameter θ corresponds to a specific cutting position. Figures 6 (a) and (b) respectively show a single cutting position and multiple cutting positions, from which the kinematical generation of tooth lengthwise curves and the tooth slots can be visualized.

Modeling of Face Hobbing Tooth Surface Generation

The face hobbing process can be implemented on the Gleason Phoenix® series CNC hypoid machines (see Fig. 8).

The machine tool settings and the tooth surface generation model can be derived based on traditional cradle-style mechanical machines. Computer codes have been developed to "translate" the machine settings, and CNC hypoid gear generators move together in a numerically controlled relationship with changes in displacements, velocities, and accelerations to implement the prescribed motions and produce the target tooth surface geometry.

In this paper, a generalized face hobbing kinematical model is developed. The proposed model, shown in Figure 9, is based on the mechanical spiral bevel and hypoid gear generators. The model consists of eleven motion elements, which are listed in Table 1. The cradle-style represents the generating gear, which provides generating roll motion between the generating gear and the generated work. In the non-generated (Formate®) process, the cradle is held stationary.

Face hobbing machine settings are: (1) ratio of roll R_a; (2) sliding base X_b; (3) radial setting *s*; (4) offset E_m; (5) work head setting X_p; (6) root angle γ_m; (7) swivel $_j$; and (8) tool tilt *i*. Although the kinematical model in Figure 9 is based on the cradle-style generators, considering the universal motion ability of CNC machines, the machine settings can be generally represented as

$$R_a = R_{a0} + R_{ac}(\varphi) \qquad (13)$$

$$X_b = X_{b0} + X_{bc}(\varphi) \qquad (14)$$

$$s = s_0 + s_c(\varphi) \qquad (15)$$

$$E_m = E_{m0} + E_{mc}(\varphi) \qquad (16)$$

$$X_p = X_{p0} + X_{pc}(\varphi) \qquad (17)$$

$$\gamma_m = \gamma_{m0} + \gamma_{mc}(\varphi) \qquad (18)$$

$$j = j_0 + j_c(\varphi) \qquad (19)$$

$$i = i_0 + i_c(\varphi) \qquad (20)$$

The first terms in Equations 13–20 represent the basic constant machine settings and the second terms represent the dynamic changes of machine setting elements, which might be kinematically dependent upon the motion parameters of the cradle rotation angle φ. Incurrent practice, higher order polynomial are used (Ref.2). These motions can be realized through computer codes on the CNC machine. Equations 13–20 provide strong flexibility for generating all kinds of comprehensively crowned and corrected bevel gear tooth surfaces.

Matrix Representation of Motion Elements

In order to mathematically describe the generation process, the relative motions of the machine elements and their relationship have to be represented by a series of coordinate transformations established and rigidly connected to each motion element listed in Table 1. In current pratice, higher polynominals are used (Ref. 2). System S_m is fixed to the machine frame 1 and is con-

Figure 8—Gleason Phoenix® II 275HC hypoid gear generator.

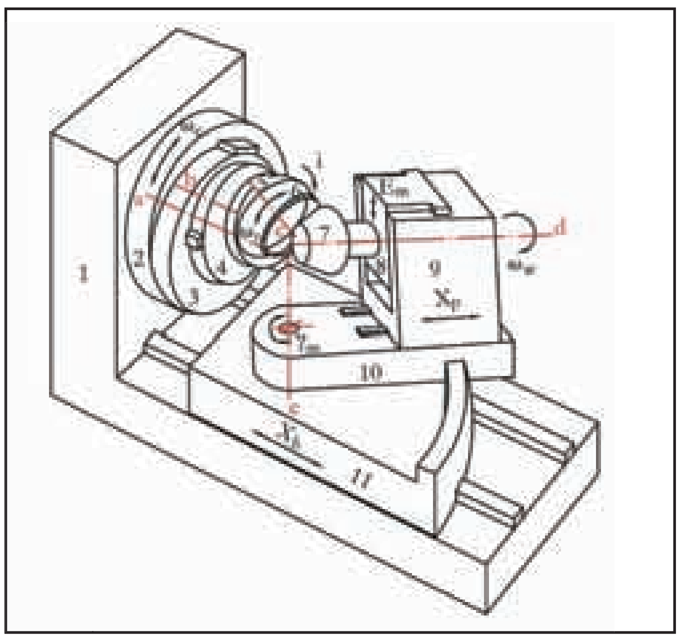


Figure 9—A kinematic model of mechanical hypoid gear generators.

Table 1—Machine Motion Elements and Axes of Rotation.

Number of motion elements	Names of elements and related motion
1	Machine frame, motion reference
2	Cradle, rotation/cradle angle
3	Eccentric, radial setting
4	Swivel, swivel setting
5	Tilt mechanism, tilt setting
6	Tool cutter/head, rotation
7	Work, rotation
8	Work support, offset setting
9	Work head setting
10	Root angle setting
11	Sliding base setting
a	Cradle axis
b	Eccentric axis
c	Cutter head/tool spindle axis
d	Work spindle axis
e	Swivel pivot axis for root angle setting

$$\mathbf{M}_{wi} = \mathbf{M}_{wo}(\psi)\mathbf{M}_{op}(E_m)\mathbf{M}_{pr}(X_p)\mathbf{M}_{rs}(\gamma_m)\mathbf{M}_{sm}(X_b)\mathbf{M}_{mc}(\varphi)\mathbf{M}_{ce}(s)\mathbf{M}_{ej}(j)\mathbf{M}_{ji}(i)$$

Figure 10—Equation 23.

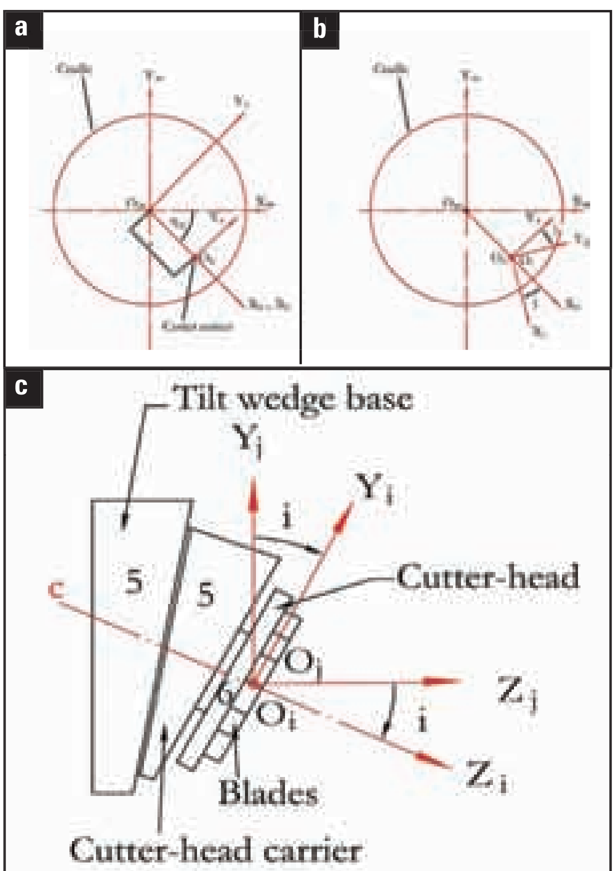


Figure 11—Relationships of coordinate systems S_m, S_e, S_j and S_i.

sidered as the reference of the related motions. System S_s is connected to the sliding base element 11 and represents its translating motion. System S_r is connected to the root angle setting element 10 and represents the machine root angle setting. System S_c is connected to the cradle and represents the cradle rotation with parameter φ. System S_p is connected to the work head sliding setting element 9 and represents the work head setting motion. System S_o is connected to the work head offset setting sliding element 8 and represents the work head offset setting motion. System S_w is connected to the work 7 and represents the work rotation with angular parameter ψ. System S_e is connected to the eccentric setting element and represents the radial setting of the cutter head (see Fig. 11 (a)). System S_j is connected to the tilt wedge base element 5, which performs rotation relative to the eccentric element to set the swivel angle j (see Fig. 11 (b)). System S_i is connected to the cutter head carrier, which performs rotation relative to the tilt wedge base element to set the tool tilt angle i (see Fig. 11 (c)).

During tooth surface generation, at each cutting instant, a point on the blade edge generates a corresponding point on the work tooth surface. Through the coordinate transformation from S_i to S_w, the current cutting point P can be represented in the coordinate system S_w, namely,

$$\mathbf{r}_w = \mathbf{M}_{wi}(\theta,\varphi,\psi)\mathbf{r}_i(u,\theta) \quad (21)$$

$$\mathbf{t}_w = \mathbf{M}_{wi}(\theta,\varphi,\psi)\mathbf{t}_i(u,\theta) \quad (22)$$

where M_{wi} (θ, φ, ψ) is a resultant coordinate transformation matrix with three parameters and is formulated by the multiplication of the following matrices representing the sequential coordinate transformations from S_i to S_w,

(see Fig. 10 for equation 23)

where matrices M_{wo}, M_{op}, M_{pr}, M_{rs}, M_{sm}, M_{mc}, M_{ce}, M_{ej} and M_{ji} can be obtained directly from Figures 12 and 13 and Equations 21 and 22 can be simply re-written as

$$\mathbf{r}_w = \mathbf{r}_w(u,\theta,\varphi) \quad (24)$$

$$\mathbf{t}_w = \mathbf{t}_w(u,\theta,\varphi) \quad (25)$$

here subscript "*w*" denotes that the vectors are represented in the coordinate system S_w.

Tooth Surface of a Non-Generated (Formate) Member

As discussed above, the non-generated (Formate) gear tooth surface is the complementary copy of the generating gear tooth surface, which is kinematically formed as the cutting path of the blade edge along an extended epicycloid lengthwise curve. In Formate gear generation, the cradle is held stationary and parameter φ is assumed to be zero. Therefore, Equations 24 and 25 can be re-written as

$$\mathbf{r}_w = \mathbf{r}_w(u,\theta) \quad (26)$$

$$\mathbf{t}_w = \mathbf{t}_w(u,\theta) \quad (27)$$

which give the position vector and a unit tangent at the current cutting point P on the gear tooth surface. The unit normal of the gear tooth surface can be derived as

$$\mathbf{n}_w = \mathbf{k}_w \times \mathbf{t}_w = \mathbf{n}_w(u,\theta) \quad (28)$$

where

$$\mathbf{k}_w = \frac{\dfrac{\partial \mathbf{r_w}}{\partial \theta}}{\left|\dfrac{\partial \mathbf{r_w}}{\partial \theta}\right|} \quad (29)$$

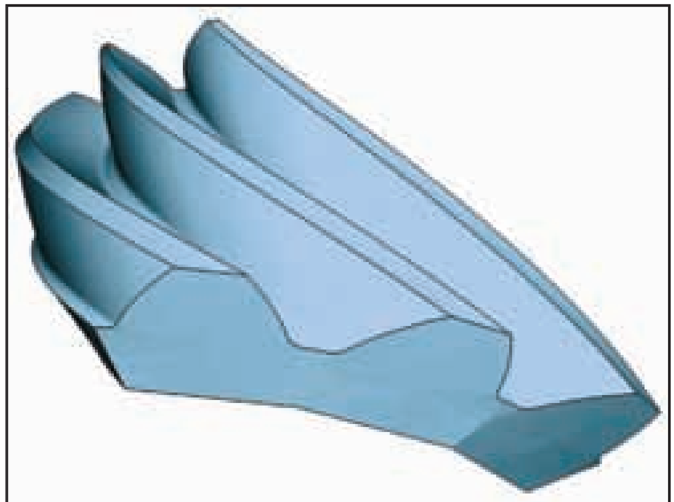
which represents the unit vector of hobbing speed. Equations 26–29 provide equations of position vector, unit tangent, and unit normal of a non-generated gear tooth surface.

Tooth Surface of a Generated Member

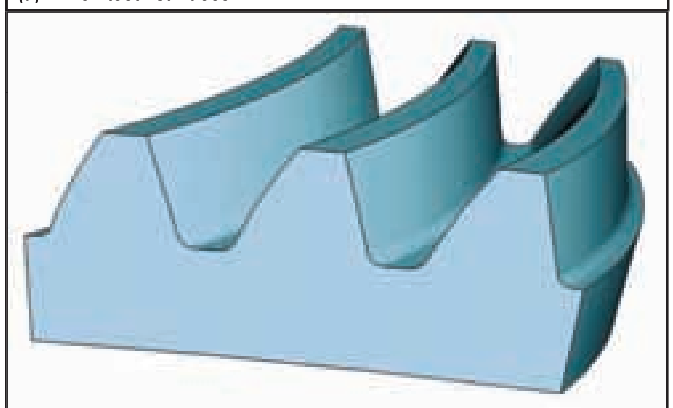
In addition to the relative hobbing motion or the indexing motion for a generated member, either gear or pinion, generating roll motion is provided and the generated tooth surface is the envelope of the family of the generating surface. The generated tooth surface can be represented as

$$\begin{cases} \mathbf{r}_w = \mathbf{r}_w(u,\theta,\varphi) \\ \mathbf{t}_w = \mathbf{t}_w(u,\theta,\varphi) \\ \mathbf{n}_w = \mathbf{n}_w(u,\theta,\varphi) \\ f_w(u,\theta,\varphi) = \mathbf{n}_w \cdot \mathbf{v}_w = 0 \end{cases} \quad (30)$$

where n_w is obtained from Equation 28,



(a) Pinion tooth surfaces



(b) Gear tooth surfaces

Figure 12—Pinion and gear tooth surfaces of a face-hobbed hypoid gear drive.

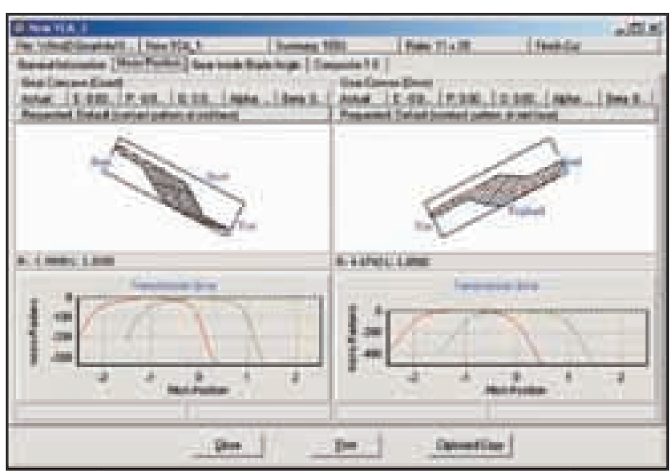


Figure 13—A TCA output interface.

and the relative generating velocity v_w is determined by

$$\mathbf{v}_w = \frac{\partial \mathbf{r_w}}{\partial \varphi}\omega_c \qquad (31)$$

Equation $fw(u,\theta,\varphi)=n_w x\ v_w=0$ is called the equation of meshing (Ref. 4). Equation 30 defines the position vector, the unit normal, and the unit tangent at the current cutting point P on the generated work tooth surface. All these vectors are considered and represented in the coordinate system S_w that is connected to the work. A unit cradle angular velocity, i.e., $\omega_c = 1$ can be considered. The equation of meshing is applied for determination of generated tooth surfaces.

Implementation of the Mathematical Models

Figures 12 (a) and (b) show geometric models of a pinion and a gear generated based on Equations 26–30. A very important application of the developed mathematical models is the development of tooth contact analysis for the face hobbed spiral bevel and hypoid gears. Tooth contact analysis (TCA) is a computational approach for analyzing the nature and quality of the meshing contact in a pair of gears. The concept of TCA was originally introduced by Gleason Works in the early 1960s as a research tool and applied to spiral bevel and hypoid gears (Ref. 7). Today, TCA theory has been substantially enhanced and generalized and applied in advanced synthesis of face milled spiral bevel gears (Refs. 8, 9).

Based on the developed mathematical models for face hobbing generation of spiral bevel and hypoid gears, an advanced TCA program for the face hobbing process has been developed for both non-generated and generated spiral bevel and hypoid gear drives. The program incorporates simulation of meshing of the whole tooth surface contact including the Toprem and Flankrem contact. Tooth edge contact simulation is also developed and included in the program. Figure 13 shows an example of the output interface of the advanced TCA. Typically, a TCA output illustrates bearing contact patterns on both driving and coast sides of the tooth surfaces and the corresponding transmission errors. Information on the gear drive assembling adjustments is also provided.

Conclusion

This paper presents the tooth surface generation theory of the face hobbing process. The kinematics of face hobbing indexing are described and simulated. A generalized spiral bevel and hypoid gear tooth surface generation model for the face hobbing process is developed with the related coordinate systems that are directly and visually associated with the physical motion elements of a bevel gear generator. The generation model covers both Gleason nongenerating and generated methods of the face hobbing process. And, it can also be adapted for the face milling process. Based on the developed mathematical model, an advanced TCA is developed and integrated into Gleason CAGE™ for the Windows system, which has been released worldwide.

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Assembling Spiral Gears: Double Taper Can Be Double Trouble

Russell Beach

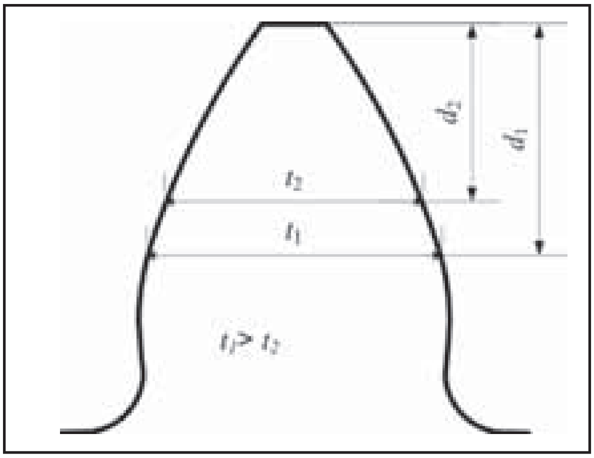

Figure 1—Spur and helical gears have significant tooth thickness taper only in the tooth depth direction.

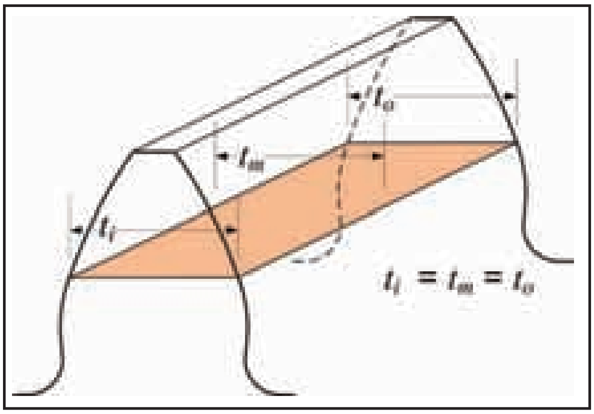

Figure 2—No tooth thickness taper in the tooth lengthwise direction.

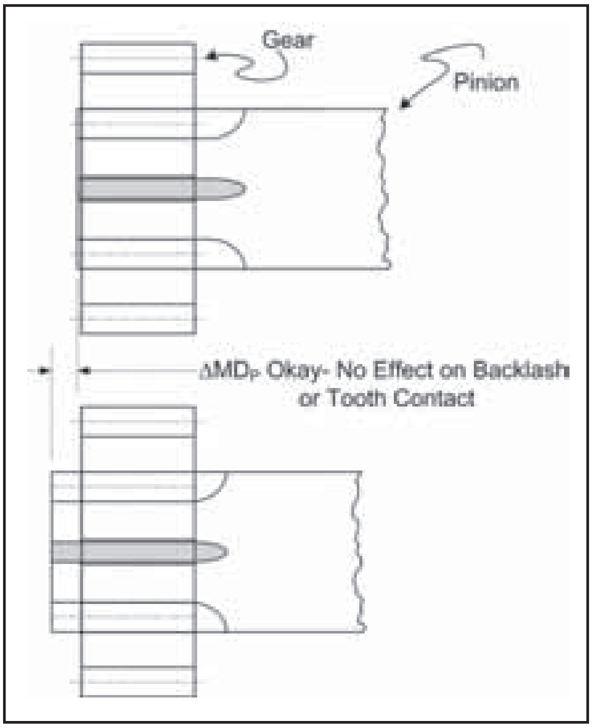

Figure 3—The axial position of the spur or helical pinion or gear doesn't affect backlash or tooth contact.

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Management Summary

Bevel gear systems are particularly sensitive to improper assembly. Slight errors in pinion or gear positioning can turn a well designed, quality manufactured gear set into a noisy, prone-to-failure weak link in your application. This article will cover basic practices in bevel assembly for optimum application. Topics discussed are limited to straight, Zerol® and spiral bevel gears without "small cutter effect." This article operates under the assumption that the housing machining is correct (offset correct, shaft angle correct, gear axis and pinion axis in correct planes) and that the bevel gears are correctly manufactured with some comments on indications to the contrary.

Tooth Taper Caper

The correct assembly of bevel gear sets (straight, Zerol or spiral) has tripped up many people unfamiliar with this gear form. The correct assembly of a bevel gear set will necessarily ensure both correct backlash and a proper mating of the tooth surfaces. A large range of pinion and gear mounting positions will provide correct backlash, but only a small range will also yield proper mating for the best noise, vibration and life. Proper mating of the tooth surfaces is indicated by a proper tooth contact. The tooth contact can be made visible in the assembly by putting a light coating of gear tooth marking compound on the teeth (with no grease or oil in the gearbox) and then rotating the parts under a light load for a few seconds. This leaves an impression in the compound, a "tooth contact pattern." In most cases, a correct light-load tooth contact pattern is one that shows the load to be carried towards the toe end of the gear teeth ("central toe contact") and within the tooth boundaries without load concentration at or near an edge. A simple comparison to cylindrical gears will point out the cause of most bevel gear assembly problems: the unanticipated effects of pinion and gear tooth taper.

Spur and helical gears have significant tooth thickness taper in the tooth depth direction (see Fig. 1), but no thickness taper in the tooth lengthwise direction, as shown in Figure 2. If the assembled center distance of a correctly manufactured cylindrical gear set is correct in a correctly manufactured housing, then the backlash will be correct even if the axial position of the pinion or gear varies slightly from nominal, as shown in Figure 3. Additionally, the tooth contact will be correct even with an axial position variation.

In the case of bevel gears, there is likewise a tooth thickness taper ("fast" taper) in the tooth depth direction, which is demonstrated in Figure 4.

Also, Figure 5 shows a tooth thickness taper ("slow" taper) along the length of the teeth. It is these tapers that can double our trouble in properly assembling a bevel gear set. If a correctly manufactured bevel gear set is assembled in a correctly manufactured housing with a pinion mounting distance error, the measured backlash will include misleading contributions from the pinion depthwise and lengthwise tooth thickness tapers, as shown in Figure 6.

If the measured backlash is within tolerance, it could lead to the erroneous conclusion that the gear set is properly assembled. However, that pinion axial position error, in addition to creating a misleading backlash reading, has a second undesirable effect—the tooth contact location has been shifted on the teeth. If the shift is not within the "adjustability range" of the gear set, which is generally only a few thousandths of an inch, the contact position can result in NVH (noise, vibration and harshness) and even tooth failure under load. A strategy that is sure to result in problems occurs if the gear set is assembled without accurate knowledge of the mounting distances with the thought of simply shimming the pinion for backlash. The resulting contact will be good only by chance.

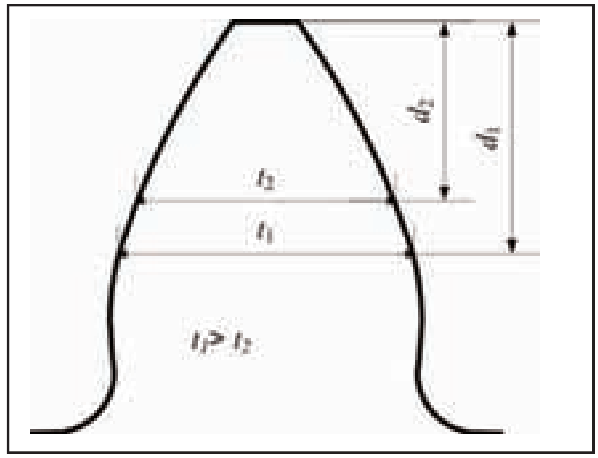


Figure 4—Like spur or helical gears, bevel gears have a tooth thickness taper in the tooth depth direction.

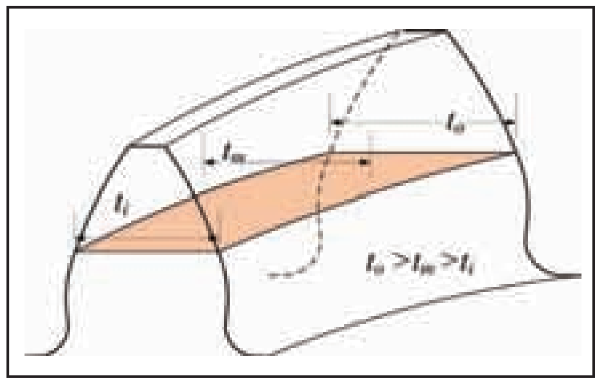


Figure 5—Bevels also have a tooth thickness taper along the length of their teeth.

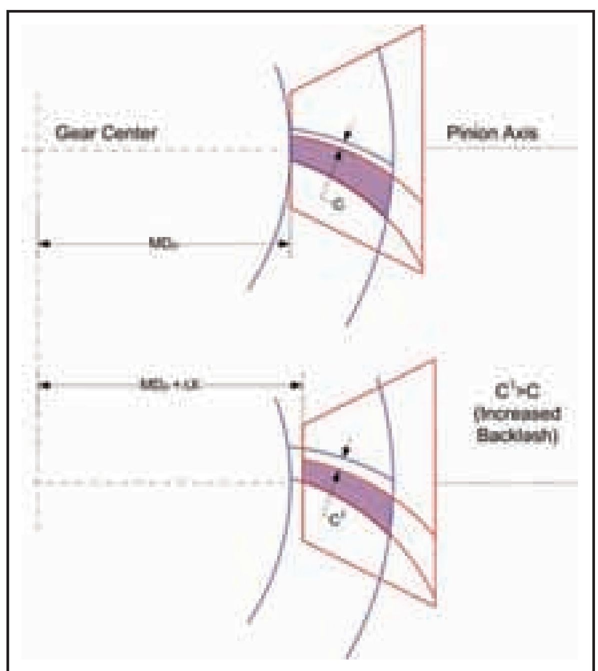


Figure 6—Misleading contributions from the pinion depthwise and lengthwise tooth tapers are apparent in this measured backlash.

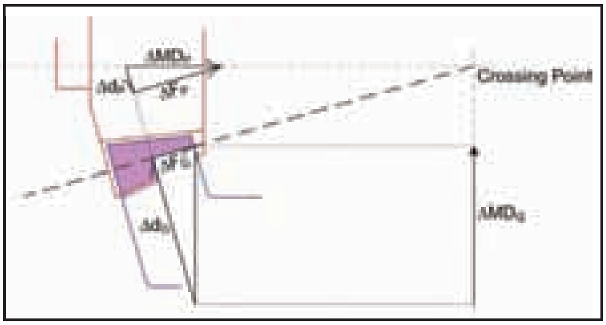


Figure 7—A cross-sectional view of a high ratio gear set.

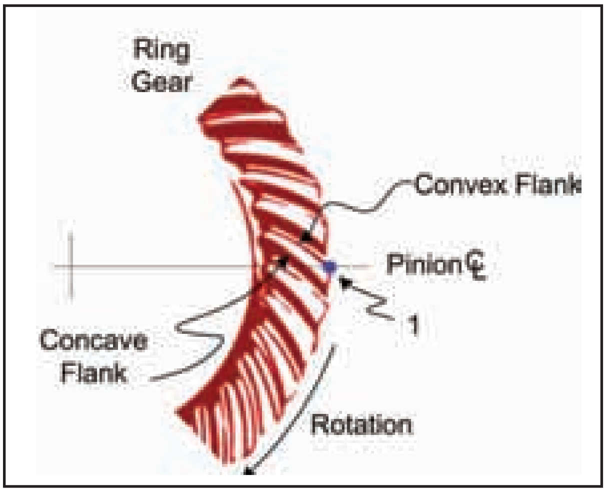


Figure 8—The pinion concave flank drives the ring gear convex flank, and the gear rotates in the direction shown.

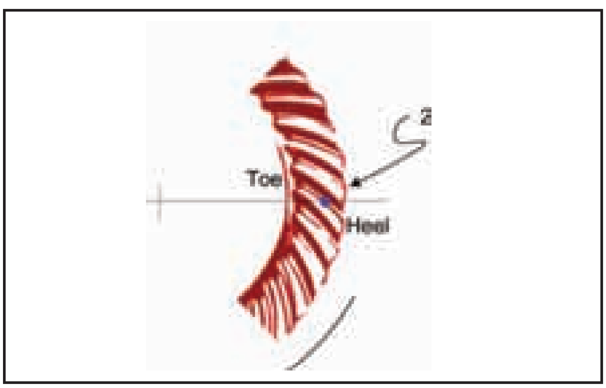


Figure 9—The contact moves along the ring gear face from the heel, over the addendum and across the dedendum near mid-face.

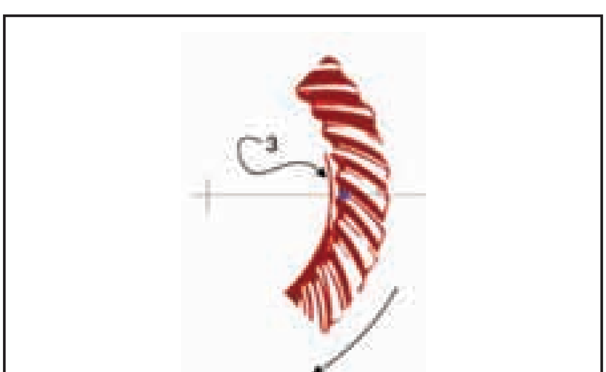


Figure 10—A final exiting engagement at the toe near the root.

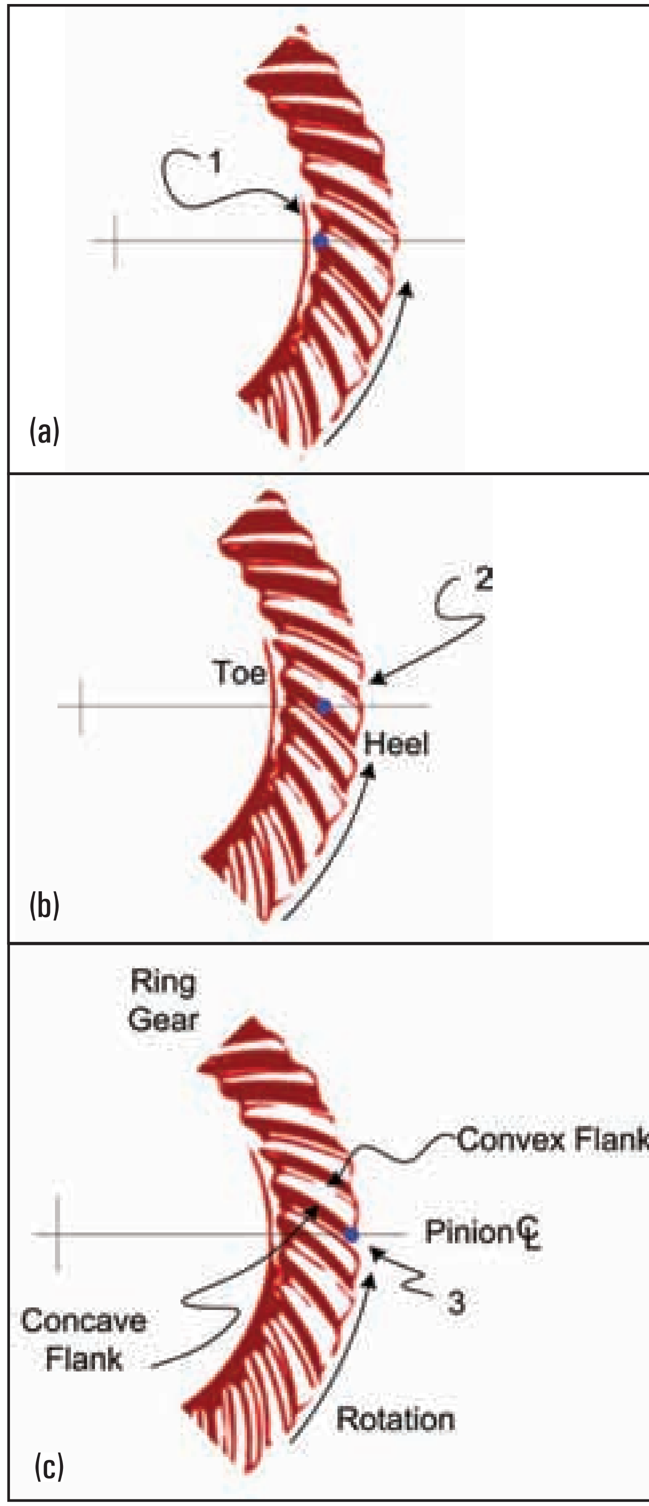


Figure 11—If the pinion direction is reversed, the top toe of the gear enters the contact zone first, with the contact moving across the face depthwise from the addendum to the dedendum and then off the tooth at the heel near the root.

To gain an understanding of what happens when the pinion is moved along its axis, look at the top of Figure 7, a cross-sectional view of a relatively high ratio gear set.

Moving the pinion axially, a small amount of ΔMDP is the same as moving it first a fractional amount ΔdP in the tooth depthwise (fast taper) direction, then secondly a relatively larger amount ΔFP in the tooth lengthwise (slow taper) direction. There is a change in backlash due to both tapers. For "high" ratios (approximately 2.5:1 and higher), experience has shown that the backlash does not change quickly with pinion axial position change. Conversely, experience has shown that the contact pattern is sensitive to movement of the pinion along its axis.

High Ratio Rule:

In comparison, moving the ring gear axially ΔMDG, shown in the bottom part of Figure 7, can be thought of as a relatively large move of ΔdG in the tooth depth (fast taper) direction plus a fractional amount of ΔFG along the length of the teeth in the slow taper direction. Consequently, it happens that the backlash is sensitive to gear axial position changes while experience has shown that the contact pattern position on the teeth is insensitive. This leads us to the following rule for ratios of approximately 2.5:1 and higher:

The tooth contact is readily affected by changes in pinion axial position. Be sure to properly position the pinion first to be assured of a correct tooth contact and to eliminate misleading tooth thickness taper in the backlash check. The backlash is readily affected by changes in gear axial position. With a properly positioned pinion, then simply adjust for backlash by moving the gear.

Contact Moves

We want to help develop a mental picture of what happens to the contact when moving the pinion. Our example is based on a spiral bevel set, but the lessons learned can be applied to straight bevel gears and Zerols as well. The standard convention for speed reducing drives is for the gear convex flank of a spiral bevel or Zerol bevel set to be the "forward driven flank" and for the concave side to be the "reverse driven flank." The pinion concave flank drives the gear convex flank, and the gear rotates in the direction shown in Figure 8.

The very first part of an engaging convex ring gear tooth surface to enter the contact zone is the top heel. The contact then moves along the ring gear face from the heel, over the addendum and across the dedendum near mid-face and off the face at the toe near the root, as shown in Figures 9 and 10.

Under load, it is convenient to think of this as a "path of contact," but it is actually a path of peak pressures. If the pinion direction is reversed, it is the top toe of the gear that enters the contact zone first, with the contact moving across the face depthwise from the addendum to the dedendum and then off the tooth at the heel near the root. This is shown in Figure 11.

Figure 12 illustrates what this path looks like in the tooth depthwise perspective.

When the pinion is assembled too close to the ring gear (the pinion mounting distance is too small), the pinion teeth are pushed into deeper mesh with the gear. The backlash is reduced. It is intuitive (and correct) that the contact will be pushed deeper into the ring gear teeth and consequently higher on the pinion teeth. The contact actually follows the path shown in Figure 13.

The contact moves deeper on both sides of the teeth and slightly crossed towards the toe on the gear concave side and towards the

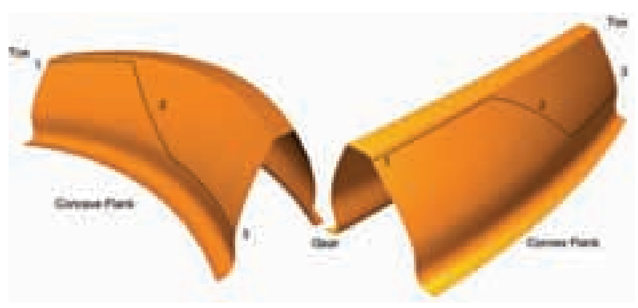


Figure 12—The tooth depthwise perspective.

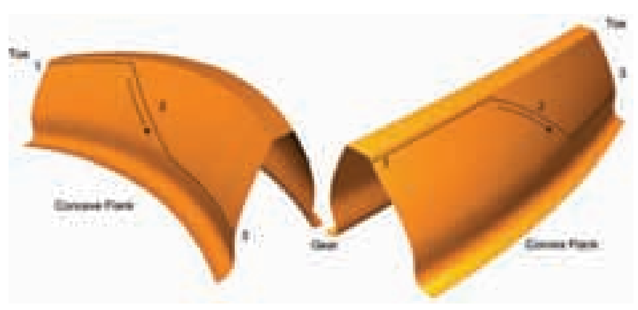


Figure 13—With the pinion assembled too close to the ring gear, the contact will be pushed deeper into the ring gear teeth and higher on the pinion teeth.

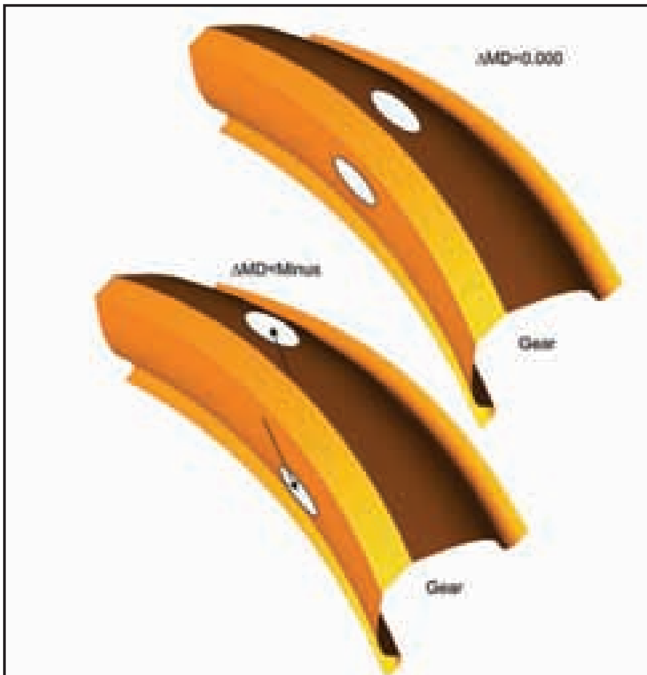


Figure 14—Changes in contact patterns with pinion assembled too close to ring gear.

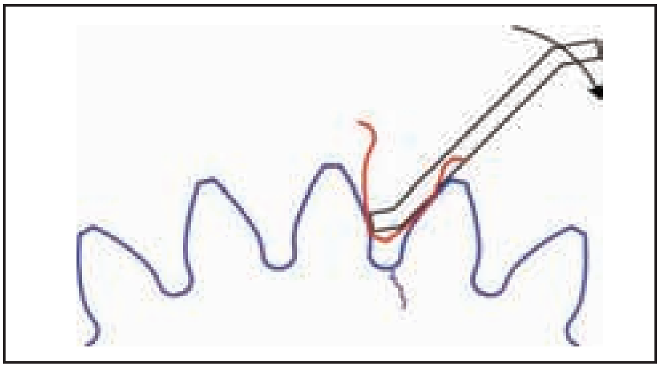


Figure 15—Tooth breakage caused by leverage resulting from insufficient backlash.

Table 1—Standard Recommended Normal Backlash for Precision Bevel Gears.	
Diametral Pitch	**Normal Backlash**
1.00–1.25	.020–.030
1.25–1.50	.018–.026
1.50– 1.75	.016–.022
1.75–2.00	.014–.018
2.00–2.50	.012–.016
3.00–3.50	.010–.013
3.50–4.00	.008–.011
4.00–5.00	.006–.008
5.00–6.00	.007–.009
6.00–8.00	.004–.006
8.00–10.00	.003–.005
10.00–16.00	.002–.004
16.00–20.00	.001–.003
20.00–50.00	.000–.002
50.00–80.00	.000–.001
80 and finer	.000–.0007

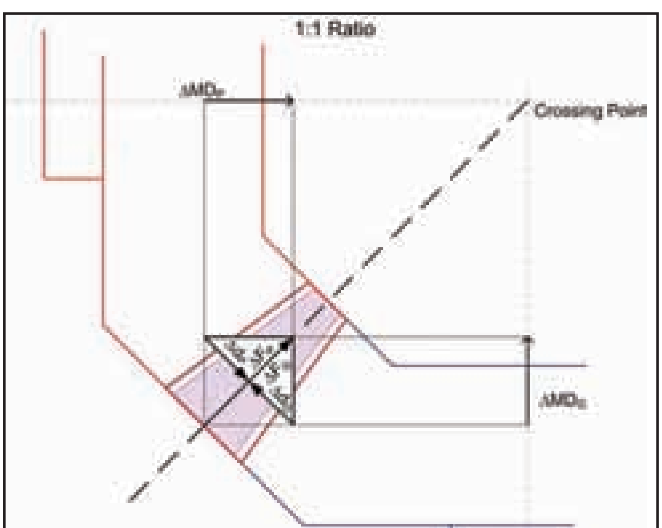


Figure 16—A low ratio diagram.

heel on the gear convex side. Figure 14 shows how the contact patterns would appear to change.

For straight bevels there is no cross, just a pure depth change. For Zerols, there is the same depth change as for spirals, but the cross is reversed, with the pattern moving toward the heel on the gear convex side and toward the toe on the gear concave side.

If the pinion is assembled too far from the gear, the patterns move in the opposite directions to those described above (for spirals, the contact will move high on the gear teeth on both sides, deep in the pinion on both sides, slightly crossed towards the heel on the gear convex and towards the toe on the gear concave).

Are You in Too Deep?

It is the depthwise contact pattern position that is the key to proper assembly. Without correct assembly, it is impossible to arrive at any meaningful judgments about the gear set or housing. If the contacts are not correct, always start by first adjusting the pinion axially to get the patterns on drive and coast sides in the correct depthwise location.

A quality bevel gear manufacturer will have carefully adjusted the position of the tooth contacts on the teeth during production. They will be in the correct position on both sides of the teeth at the nominal mounting dimensions and with the correct amount of backlash. Importantly, the contact will not be "lame" (high on the teeth on one side and low on the teeth on the other) or "crossed" (towards the toe on one side and towards the heel on the other). These are conditions that cannot generally be compensated for in assembly.

Backlash Woes

Just as a pinion mounting distance error can have unwanted side effects leading to NVH or tooth breakage, there can be undesirable side effects if the backlash is set incorrectly. The gear teeth need backlash to allow the teeth to roll in and out of mesh without the reverse sides of the teeth coming into rubbing contact. With proper backlash, a correctly made gear set will roll smoothly by hand, with no "stick-slip" feeling. If the backlash is insufficient, that same correctly made gear set will have tight spots. These can easily be felt when hand rolling the gear set. The rolling motion will be rough, with a jerky stop-and-go action. The tight spots occur due to high points of runout and tooth errors in the pinion and gear coming together. Under load, the gears will be noisy, vibrate and may run hot. If the backlash is reduced still further, it is possible for the friction to become so great that the teeth will wedge together. The leverage that is applied by the load to the wedged teeth can actually cause the teeth to break, shown in Figure 15.

A generally less visible problem can occur at assembly if the backlash is too great. Too much backlash is caused when the ring gear teeth are positioned out of mesh from their correct location or, worse, when the pinion is too far out of mesh. The overlapping action of the gear teeth is reduced and the load is carried higher on the ring gear teeth, compromising the load sharing of the teeth. Reduced load sharing and higher load position on the teeth results in higher tooth stress. This can lead to premature tooth failure.

Too much backlash can lead to mesh frequency noise (primarily if the pinion is out of position) and "tooth rattle" or "clunk" noises. Tooth rattle is excited by gear tooth errors or other sources of pulsing in the drive train acting to cause flank reversals through the clearances between the teeth. The sound can be grating and very irritating. It strikes multi-stage gearing more readily than single-stage and may, significantly, exhibit no harmonic frequency content when the sound is processed through a spectrum analyzer. Reducing the amount of backlash in the gear train and reducing the strength of the pulsing by improving the gear quality (runout, accumulated pitch error) are the approaches generally taken to alleviate this condition.

Standard recommended "normal" backlash for precision bevel gears is broken down in Table 1.

"Normal" here does not mean "regular." Normal is an engineering term meaning "at right angles to." In this case, it means at right angles to the spiral angle and the pressure angle at the heel end of the gear teeth at about mid-tooth depth. A dial indicator is used to measure the normal backlash. This is not always convenient when the gears are in the assembly. A convenient and accurate way to check the backlash in an assembly is to measure the backlash "in the plane of rotation." This can be accomplished by attaching a simple lever to the end of an accessible pinion or gear shaft. The dial indicator should be positioned so that the probe is contacting the lever at approximately the pitch radius of the teeth. The conversion from plane of rotation backlash (PRB) to normal backlash (NB) is:

NB = PRB x Cosine(Spiral Angle) x Cosine(Pressure Angle)

The actual backlash that we use for manufacturing is the backlash range specified on the customer's part drawings with the parts positioned in a rolling gear tester at the gauged print nominal mounting distance. The backlash specified on the part drawings must take into account the mounting distance variations that come from the assembly tolerance stackup if selective fit shims are not used. Sometimes backlash larger than the standard recommended backlash is required to accommodate the tolerance stackup. Equations 1 and 2 are formulas for calculating the change in backlash to be expected for a given mounting distance change, either for the pinion or the gear.

$$\Delta MD_p = \frac{\Delta B_p}{2\tan\phi\sin\gamma} \quad (1)$$
$$or\left[\Delta B_p = \Delta MD_p * 2\tan\phi\sin\gamma\right]$$

$$\Delta MD_G = \frac{\Delta B_G}{2\tan\phi\sin\Gamma} \quad (2)$$
$$or\left[\Delta B_G = \Delta MD_G * 2\tan\phi\sin\Gamma\right]$$

These formulas are useful for estimating shim thicknesses for a backlash adjustment. An example is given for a 3.545:1 ratio.

Example:
11 x 39 combination and 9.25 Diametral Pitch
Pressure angle ϕ =20°
Pinion pitch angle γ = 15.75°
Gear pitch angle Γ = 74.25°

How much does the backlash change if I move the pinion –0.005" (ΔMDP = –.005") or if I move the gear – 0.005" (ΔMDG = –.005")?

ΔBP = –.005 ∗ 2 tan 20°sin15.75° = –.0010" reduction in backlash

ΔBG = –.005 ∗ 2 tan 20°sin 74.25°= –.0035" reduction in backlash

Notice that the backlash change is three to four times as fast for a gear mounting distance change as for the same amount of pinion mounting distance change.

Special Considerations For Assembling Low Ratio Gear Sets

What if the ratio is not higher than 2.5:1 as discussed above?

The assembly has an extra step in it for ratios from 1:1 to approximately 2.5:1. As before, assemble the pinion and gear with backlash and check the tooth contact pattern. Shim the pinion in or out of mesh to put the pattern in the correct depthwise position on the teeth. Next, it is necessary to adjust for the correct backlash. This is where the assembly procedure changes. It is necessary now to move both the pinion and gear for the backlash adjustment in order to keep the contact pattern from moving out of position. Refer to Figure 16, a diagram similar to that of Figure 7, but now for a low ratio (1:1).

A small axial move of the pinion is represented again by a component in the depth direction and a component in the face direction. Now these components are equal. Also, the components for the gear are the same as those for the pinion for the 1:1 ratio.

The necessary pinion shim change will be related to the gear shim change by the ratio. So, if the ratio is 1:1 and the gear will be moved into mesh 0.005", then the pinion must be moved into mesh 0.005" to maintain the correct pattern. If the ratio is 2:1, a 0.005" gear shim change would be accompanied by a 0.0025" pinion shim change. You can use the calculations in Equations 1–2 to estimate the shim thickness changes. The relationship between the pinion and gear shim, mathematically, is:

Ratio = M = (number of gear teeth divided by number of pinion teeth)
Gear shim thickness change = (X.XXX)
Pinion shim thickness change = (X.XXX/M)

For low ratios, we can summarize as follows.

Low Ratio Rule:

The tooth contact is readily affected by changes in both pinion and gear axial position. Properly position the pinion first (or the gear if the backlash is close to 1:1) to be assured of a correct tooth contact and to eliminate misleading tooth taper thickness in the backlash check. The backlash is readily affected by changes in both gear and pinion axial position. Adjust second for backlash by moving the pinion and gear in proportion to the ratio.

Are You Hunting for Backlash?

When there is no common factor between the number of teeth in the pinion and gear, the ratio is said to be "hunting tooth." This kind of design could also be called "hunting backlash"! Ratios of this type require the greatest number of revolutions of pinion and gear before all pinion teeth have meshed at least once with each gear tooth.

Example: Ratio 2 x 3 (n x N combination)

As the pinion rotates with the gear, the pinion teeth match up with the gear teeth in a pattern that eventually repeats:

Pinion <u>1 2</u> <u>1 2</u> <u>1 2</u> 1 (pinion teeth are numbered 1 and 2)
Gear <u>1 2 3</u> <u>1 2 3</u> 1 (gear teeth are numbered 1, 2 and 3)

The gear requires two (which is "n") rotations, the number of

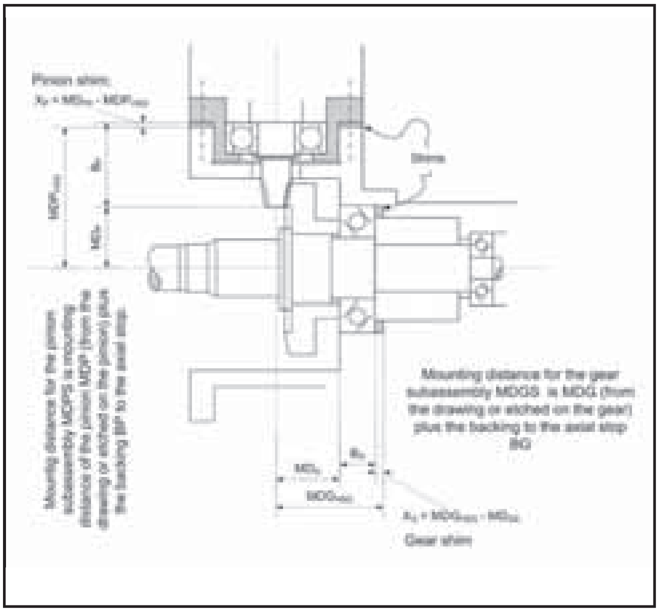


Figure 17—Gauging and shims in assembly.

teeth in the pinion, for all gear teeth to see all pinion teeth. The pinion requires three ("N") rotations

For a practical example, consider an 11 x 39 combination. From above, 11 gear rotations are required for all gear teeth to see all pinion teeth. Or 39 pinion rotations are required for all pinion teeth to see all gear teeth. Question: When you assemble your gears, do you check four places on 11 rotations (that would be 44 points) of the gear? Not likely. Most assemblers check only four places on one rotation of the gear, or even less. How about 429 places? For the 11 x 39 combination, there are actually 11 x 39 = 429 unique mesh points. It is impractical to check all these mesh points for backlash in assembly. The point is in most cases, the true minimum backlash in assembly is not located. Consequently, when dealing with a hunting tooth ratio assembly, it is wise to assemble with a backlash check a little above the minimum backlash specification.

The Rest of the Story

The mounting distance given on the pinion and gear drawings is only a part of the assembly story. The pinion is generally built up on a subassembly that yields a stackup of axial tolerances. There is a tolerance at each axial interface from the pinion mounting distance surface to the final locating surface on the subassembly that will contact the axial stop in the housing. This constitutes the pinion subassembly mounting distance MD_{PS} +/–0.www. The same is true for the gear resulting in the gear subassembly mounting distance MD_{GS} +/–0.xxx. The housing itself has a mounting distance to the axial stop for the pinion (pinion housing mounting distance MDP_{HSG} +/–0.yyy) and for the gear (gear housing mounting distance MDG_{HGE}+/–0.zzz). Adding the tolerances tells us the total stackup to expect. For a small number of subassembly and housing interfaces, simply adding the individual tolerances to establish a stackup is adequate. For a larger number of interfaces, a statistical average may be used to more realistically estimate the range of positions the teeth might actually experience. If you do not plan on using shims, it is very important to consult your bevel gear manufacturer about the stackup you expect to have. The manufacturer can comment on the practicality of developing the gear teeth to accommodate the range.

For a specific subassembly going into a specific housing, the difference between the subassembly mounting distance and the housing mounting distance is the shim size "x" to use (Fig. 17). Here is a summary of three common assembly procedures.

Gauging and Shims. Gauge the housing mounting distance for the pinion, gauge the pinion subassembly mounting distance; the difference between the two is the shim thickness to be used to locate the pinion. Repeat for the gear or selectively shim the gear to the backlash specification. This approach is used for high quality industrial gearmotor assemblies, for example.

Stackup without Shims. Design the housing and subassembly stackup of tolerances that affect the pinion and gear mounting locations so that the stackup is within the adjustability range of the bevel gear set. Additional backlash may be required. This approach is common for high volume production of many hand power tools. Be sure to consult with your bevel gear supplier about the stackup you expect the gears to accept.

Trial and Error with Shims. Assemble the pinion and the gear with adequate backlash and no lubrication. Mark the gear set with gear tooth marking compound. Roll the gear set at light load (apply some resistance) for an initial pattern check. Carefully observe the pattern with good lighting, comparing the patterns on the gear convex and concave surfaces to each other and on the pinion concave and convex surfaces to each other. Pay particular attention to whether the contacts are high on both sides of the gear or low on both sides of the gear and use the patterns on the pinion as a cross check. If low on both sides of the gear, the pinion is mounted too close to the gear center. The corrective action is to shim the pinion out. If the contact is high on both sides of the gear, the pinion is located too far from the gear center. Shim the pinion closer. For fine pitch gears in the range of 25 diametral pitch to 16 diametral pitch, a suggested starting place for a shim change is 0.002". Next shim as necessary to meet the backlash specification. This assembly approach is used for low volume production.

It is critical to note that all of the above procedures rely on the pinion being properly located first so that the tooth contact will be correct. This is a precursor to having the smoothest, quietest running quality possible from the given parts. This also guarantees that the measured backlash will not have any misleading contribution from the pinion tooth tapers. Once the contact is assured as correct, it is safe to adjust the gear and pinion as necessary to the backlash specification.

Remember the Key:

The key to adjustment is to check the depthwise position of the contacts on the drive and coast sides of the gear teeth.

Remember the rule:

Adjust the pinion axially for an acceptable contact pattern and to eliminate misleading pinion tooth thickness in the backlash check. Then adjust, according to ratio, for the correct backlash.

But There's Still a Problem

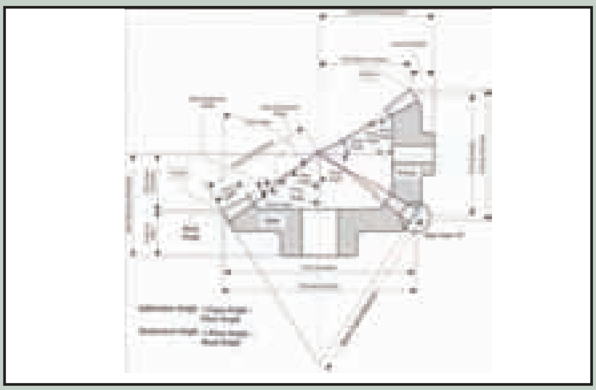
If the pinion is known to be properly positioned, the backlash is correct and a tooth contact check reveals unacceptable contact patterns, then what?

If the contact patterns are "lame," deep on the gear tooth on one side and high on the gear tooth on the other, the gear set manufacturing must be seriously questioned. It is not possible to compensate for a lame bearing in assembly, since a different pinion mounting distance from forward to reverse operation is indicated. Proper machining of the gear set can be readily confirmed by a quality gear supplier. The supplier has only to set up a gear rolling checker to the print mounting distances and offset and send you an electronic photograph of the contact patterns.

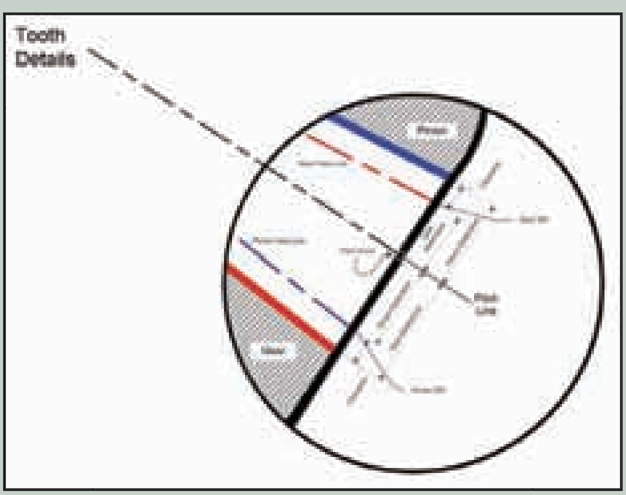
If the contact patterns are "crossed," meaning toward the toe end of the teeth on one side and toward the heel on the other, and the pinion has already been shimmed so the patterns are not high or low on the gear teeth, an offset error is indicated. There are two places to look. The gear set could have been incorrectly manufactured with a non-zero offset (this can happen, for example, as a consequence of an improperly gauged gear rolling tester, one incorrectly set up with a non-zero offset). The gear set can be readily confirmed as mentioned above by a quality supplier with a contact check in a correctly gauged gear rolling tester. Alternatively, there could be a housing problem. There could be an offset error in the housing, so that the pinion axis and the gear axis do not intersect at the crossing point. The axes would not be in a common plane. Another housing error possibility is that the pinion axis is pitched forward up or down—tipped—in the plane transverse to the gear axis.

Not all possible conditions and situations have been covered in this paper. We have endeavored to cover the most basic and most common items. We've also made an effort to provide an understanding of the underlying nature of bevel gear teeth to provide you with a foundation of knowledge rather than just charts and diagrams to reference.

Bevel Gear Terminology Basics

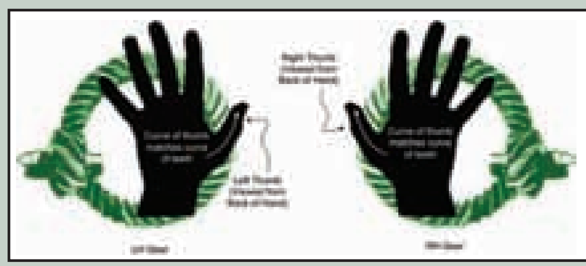


Above is an axial section of the general case for Zerol and spiral bevel gears. The root lines as shown are not correct for the case of straight bevel gears. For straight bevel gears, the root lines pass through the pitch apex (crossing point of the pinion and gear axes).



Spiral Angle: Angle between a line through the gear center and the tangent to the tooth surface at the tooth mid-face.

Hand of Spiral Convention: A left-hand gear always mates with a right-hand pinion. A right- hand gear always mates with a left-hand pinion. The "rule of thumb curvature" shown below can be applied to either the pinion or the gear and works for Zerol bevels, spiral bevels and hypoids. The gear or pinion is positioned so you are looking down the axis with the teeth toward you and with your hand facing palm-down.



Cutter Diameter Size and "Small Cutter Effect": As the size of the cutter used to produce a spiral bevel gear becomes "small" relative to the size of the ring gear, the behavior of the tooth contact pattern with respect to displacements of the pinion or gear changes. This article deals with the assembly of the common "large cutter diameter" spiral bevel gears found in most small spiral bevel gear applications. For conventionally designed spiral bevel gears (35° spiral angle, face width approximately 1/3 of the outer cone distance), if the cutter radius is larger than 0.65 times the outer cone distance [outer cone distance = (0.5 times pitch diameter of the ring gear) divided by (sine of the ring gear pitch angle)], there should be no "small cutter effect" present.

Investigation of the Noise and Vibration of Planetary Gear Drives

Yong Chen and Akira Ishibashi

Dr. Yong Chen *is in charge of research and development of gear mechanics for car automatic transmissions in the engineering development center of JATCO Ltd., located in Fuji-shi, Japan. His work mainly involves research on the noise, vibration and power transmission efficiency of the planetary gear mechanism of automatic transmissions and research into contact fatigue strength of carburized gears that have undergone tooth surface modification.*

Dr.-Eng. Akira Ishibashi *is an emeritus professor at Saga University, located in Saga, Japan. He's designed and made a superprecise gear grinding machine with a CBN grinding wheel, capable of mirrorlike finishing. He's also designed and made a large capacity testing machine capable of applying loads on teeth during rotation of test gears. He's a member of the American Society of Mechanical Engineers and of the Japan Society of Mechanical Engineers.*

Management Summary

With the aim of reducing the operating noise and vibration of planetary gear sets used in automotive automatic transmissions, a meshing phase difference was applied to the planet gears that mesh with the sun and ring gears. Shaved and hardened helical gears with and without grinding were used as the component gears for testing under varying rotational speeds and tooth loads. The experimental results clearly showed that planetary gear set noise and vibration were reduced when a meshing phase difference was applied.

Introduction

Along with the dramatic penetration of passenger cars with automatic transmissions in recent years, there have been ever-increasing demands for enhanced interior quietness, which is an important factor influencing occupant comfort. This situation has further heightened the need to reduce gear noise. Reducing planetary gear set noise is a key issue in the attainment of quieter-operating automatic transmissions. Meshing of the gears in the planetary gear set that forms the ratio-changing mechanism of an automatic transmission produces gear noise over a wide range of driving conditions from low to high vehicle speeds. However, such gear noise often becomes a problem in the relatively low load region. Because noise is judged on the basis of perception, it is difficult to set targets for reducing noise levels. It is expected that noise issues will continue to require ceaseless R&D efforts in the coming years (Ref. 1).

In this study, the relationship between the meshing phase difference and torsional vibration of planet gears was investigated from the standpoint of their rotational meshing cycle. Using planetary gear sets with and without a meshing phase difference, measurements were made of their noise and vibration acceleration under various driving conditions. The method of finishing the gears, the tooth profile contact ratio and other factors were varied in order to compare and analyze the measured data.

Examination of Meshing Phase Difference and Torsional Vibration

Torsional vibration of planetary gear set. In examining planetary gear set vibration, it is necessary to consider the forces that vary in the direction of rotation (torsional vibration) and in the radial direction (bending vibration). Several planet gears are generally positioned on a carrier at the same pitch. The number of teeth in the planet gears and the gear position on the carrier determine whether the planet gears all begin to mesh simultaneously or at different times. It is presumed that the number of teeth in the planet gears has traditionally been determined so as to balance the varying forces in the radial direction because that balancing facilitates easier gear design. In other words, all of the planet gears begin meshing simultaneously.

Based on the noise measured in an actual vehicle interior, it is thought that the meshing excitation forces of gear pairs in the planetary gear set of an automatic transmission are mainly the effect of torsional vibration in the direction of rotation (Ref. 2). In general, meshing excitation forces between the ring gear and the planet gears, however, are relatively smaller than those between the sun gear and the planet gears (Ref. 3). That is because the rim of the ring gear in a planetary gear set undergoes large deflection on account of its thinness. Dynamic loads having the same characteristics occur between the sun gear and the planet gears, but when there is meshing phase difference between the gears, meshing excitation forces differ by an amount equal to the difference in the timing at which the meshing of each planet gear begins.

The concept of a meshing phase difference between the sun gear and the planet gears of a planetary gear set is illustrated schematically in Figure 1. It is assumed that there is no meshing phase difference at the onset of meshing by the dedendum of a planet gear (1) and the addendum of the sun gear (point Q_1 in the figure) and the onset of meshing by the dedendum of a planet gear (2) and the addendum of the sun gear (point Q_2).

Accordingly, the rolling angle $\Delta\theta$ of the sun gear from point Q_3 at which it actually meshes with the planet gear (2) to point Q_2, where there is no meshing difference, becomes the angle of the meshing phase difference. Here, we will let Z' denote the remainder obtained when the number of teeth of the sun gear is divided by the number of planet gears, n. Then, the phase difference $\Delta\theta$ at the time the teeth of the j-th planet gear begin to mesh with the teeth of the sun gear can be given by the following equation in relation to the term for the k order of the meshing frequency components.

$$\Delta\theta = kj\left(2\pi Z'/n\right) \qquad (1)$$

It is assumed that the process of change in dynamic loads from the onset to the conclusion of meshing by the teeth of each planet gear is completely equal. The meshing excitation force (tangential force F_{kj}) applied to the sun gear when it meshes with the j-th planet gear can be expressed as a sine wave in relation to the term for the k order and is given by the following equation (Refs. 4–5).

$$F_{kj} = F_{nkj} \sin k\left[\omega t + j(2\pi Z'/n)\right] \qquad (2)$$

where F_{nkj} is the amplitude. Accordingly, the moment based on the k-order dynamic load applied to the sun gear by each planet gear is a variable component having a simple sine wave form with a cycle of one tooth pitch and can be given by the following equation if its amplitude is equal.

$$\sum M = \sum M_k = \sum_{j=1}^{n} F_{kj} R_o \cos\alpha_n = F_{nk} R_o \cos\alpha_n \sum_{j=1}^{n} \sin k[\omega t + j(2\pi Z'/n)] \qquad (3)$$

where F_{kj} is the meshing excitation force of the

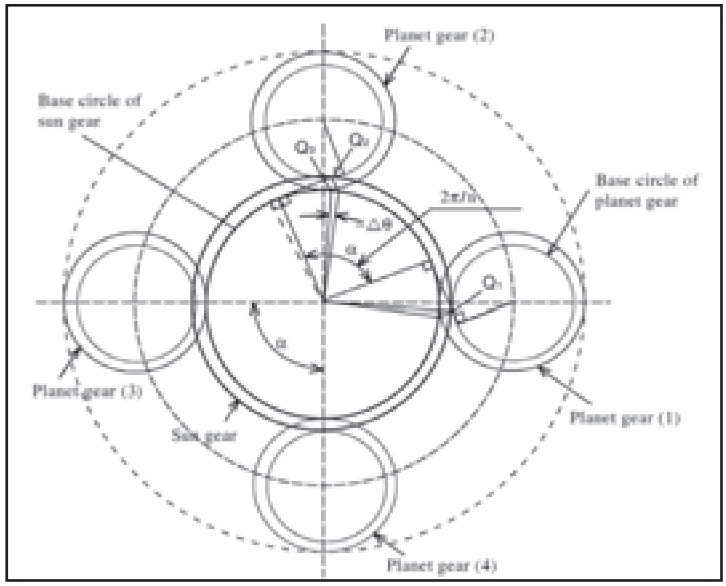


Figure 1—Schematic diagram of meshing phase difference in a planetary gear set with four planet gears.

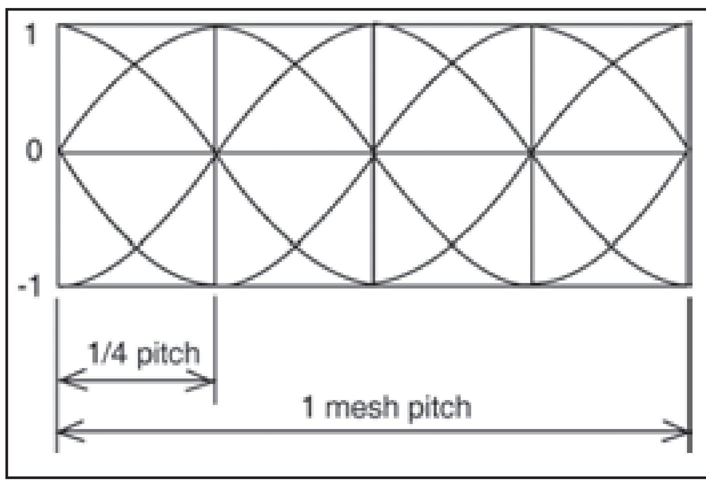


Figure 2—Elimination of exciting forces caused by four planet gears.

planet gears, R_o is the radius of the pitch circle of the sun gear, α_n is the normal pressure angle of the teeth and k is the order of the meshing frequency components. In general, when (kZ_A/n) is not an integer, $M_k = 0$, where Z_A is the number of teeth of the sun gear.

Phase difference design for planetary gear set. In a planetary gear set, the meshing relationship of sun gear teeth that mesh simultaneously with planet gears can be given a different phase depending on the selection of the number of sun gear teeth and the positional angle of the planet gears. Creating this phase difference involves selecting a suitable number of teeth for each gear in relation to the number of planet gears, n. In designing the meshing phase difference, the conditions for determining the number of teeth in the planet gear pairs are given by the following equations.

$$(Z_C + Z_A)/n = m \qquad (4)$$

$$Z_A / n \neq m \qquad (5)$$

where Z_A is the number of teeth in the sun gear, Z_C is the number of teeth in the ring gear, n is the number of planet gears and m is an arbitrary integer.

Using Equations 4 and 5 makes it possible to provide a meshing phase difference of $1/n$ pitch at the meshing position of each planet gear with the sun gear even if the planet gears are spaced equally. If the number of teeth is selected according to the conditions in Equations 4 and 5, the meshing of the sun gear and the planet gears and that of the planet gears and the ring gear will all have a different meshing phase. Accordingly, rotational variation induced by meshing in the direction of rotation, which is one factor causing vibration based on the meshing cycle, should theoretically be 0 because the varying components of the overall stiffness of the teeth pairs differ mutually in phase and are completely balanced (Ref. 2).

A rotational variation of theoretical 0 is thought to be the reason why vibration in the direction of rotation is markedly reduced when the planet gears and sun gear mesh. In a planetary gear set with a meshing phase difference in the direction of rotation, force changes induced by the planet gears in the radial direction relative to the sun gear are considerably smaller. However, if necessary, it is possible to design a meshing phase difference in both the rotational and radial directions.

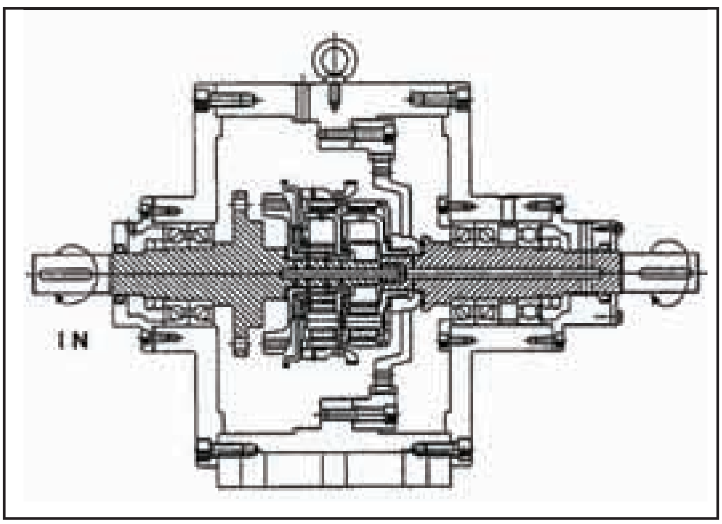


Figure 3—Axial section of a planetary gear set testing machine.

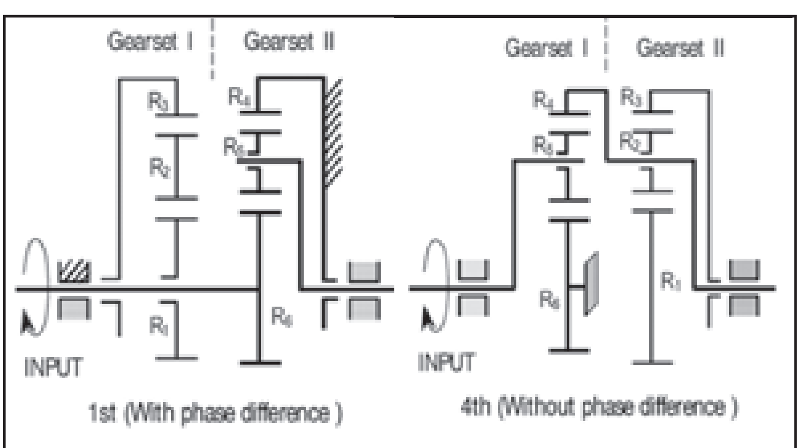


Figure 4—Schematic diagrams of planetary gear sets.

Figure 2 shows the change in excitation forces in a planetary gear set that was given a meshing phase difference in this study. This diagram makes it easier to understand the effect of the meshing phase difference. It is assumed here that the meshing excitation force applied by each planet gear can be transformed to a simple sine wave having a cycle of one tooth pitch. It is also assumed that the amplitude and cycle between each of the planet gears are the same, which results in the excitation forces being completely cancelled out by the meshing phase difference, as is seen in this figure.

Using the equation proposed by Suzuki, et al. (Ref. 6), the rotational transmission errors of planetary gear sets with and without meshing phase differences were calculated, assuming that there were three or four planet gears. For both three and four planet gears, the calculated rotational transmission error was reduced to one-thirtieth of its original value by applying a meshing phase difference, assuming that each gear had the same level of accuracy. (A detailed explanation of the calculated results is omitted here.) It is thought that the number of planet gears has substantially less influence on vibration and noise than the meshing phase difference design.

Experimental Apparatus and Procedure

Planetary gear set testing machine. Figure 3 shows an axial cross section of a prototype planetary gear set testing machine that was designed and built in this study for the purpose of measuring the noise and vibration of each planetary gear set separately in each speed range of automatic transmissions in use on production vehicles. The stationary and mating parts are provided with joints having an internal spline. This provision enables the mating parts to move to a position of equal meshing when the load torque is applied, so the load acts uniformly.

The machine is designed such that the stationary parts and planetary gear sets for an automatic transmission can be tested separately in each speed range. By changing the method of coupling the planetary gear set, the method of locking the primary shaft, the switching of gears between drive and driven states and other conditions, the machine can switch among four gear ratios just like an actual transmission used in a passenger car. Figure 4 shows a schematic diagram of a transmission built with two planetary gear sets, one without a meshing phase difference (denoted as gear set I) and one with (denoted as gear set II).

Experimental apparatus. The schematic diagram in Figure 5 shows the arrangement of the measuring devices for the power-absorbing type of gear load testing machine used in the experiments. Rotational speed and input and output shaft torque were measured under an applied load with an electronic speed meter and strain gauges, respectively. As indicated by the dashed lines in the figure, the drive motor, continuously variable transmission and planetary gear set testing machine were enclosed in soundproof boxes, which reduced background noise by approximately 6 dB.

Test gears. The specifications of the gears of the planetary gear sets used in the experiments are given in Table 1. Planetary gear set I did not have a meshing phase difference, whereas planetary gear set II did. Two types of sun and planet gears were used. One type was shaved and hardened by carburization only; the other type was ground on a Maag gear grinder following hardening. The accuracy of the former type was JIS class 3–4, and the maximum height (R_y) of the tooth surface roughness profile was approximately 6 μm. The accuracy of the ground gears was JIS class 0–1, and the maximum height (R_y) of the tooth surface roughness profile was approximately 2 μm.

As indicated in Table 1, two types of planet gears and sun gears having different addendum circle radii were used to vary the transverse contact ratio. The test gear pairs came from the same manufacturing lot as mass-produced gears, and an effort was made to select ones having tooth face geometries that were as uniform as possible. Care was taken to achieve the same experimental conditions by measuring the accuracy of the tooth shape and tooth trace of all the test gears and the planet gear shaft hole position accuracy and layout accuracy of the carriers for assembling the planet gears.

Experimental procedure. The abovementioned two types of planet gears and sun gears having different tooth shape meshing ratios and finished with different processing methods were installed in the planetary gear set testing machine, and tests were run with the lubrication oil temperature set at 32° ±2°C. The flow rate of the lubrication oil was set at 1.5 L/min, and the oil was circulated by means of an oil pump. The lubrication oil used was a commercial automatic transmission fluid.

The vibration acceleration and noise levels of the planetary gear sets were measured in an input torque range of 0–80 Nm and an input shaft speed range of 500–2,400 rpm, with the rotational speed varied in increments of 100 rpm. Two acceleration pickups were attached near the bearings that supported the input and output shafts. A stationary noise meter for measuring the noise level (characteristic A) was positioned 60 mm from the top of the planetary gear

Table 1—Specifications of Gears Used for Planetary Gear Sets.

	Planetary gear set I			Planetary gear set II		
	Sun	Planet	Ring	Sun	Planet	Ring
Number of teeth	33	21	75	37	19	75
Module (m_n)	1.23			1.23		
Pressure angle (deg)	20°			20°		
Number of planets	3			4		
Helix angle (deg)	23.3°			23.3°		
Profile contact ratio (A)	1.65	1.84		1.65	1.81	
Profile contact ratio (B)	1.31	1.69		1.30	1.66	

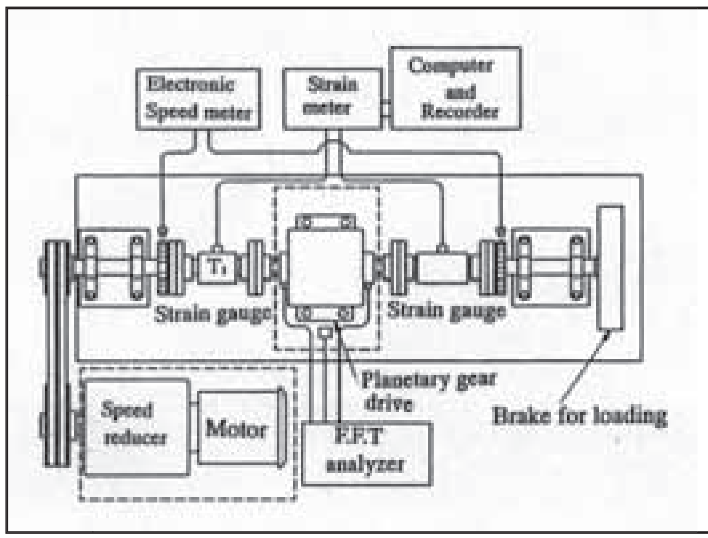


Figure 5—Gear set testing system.

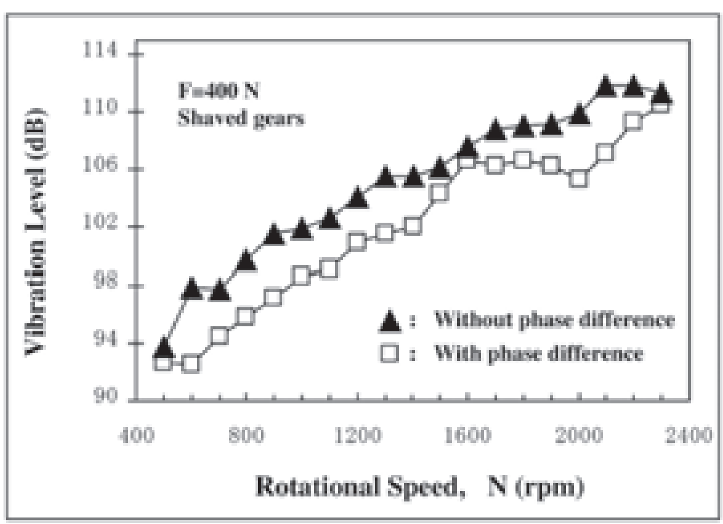


Figure 6—Effect of meshing phase difference on vibration.

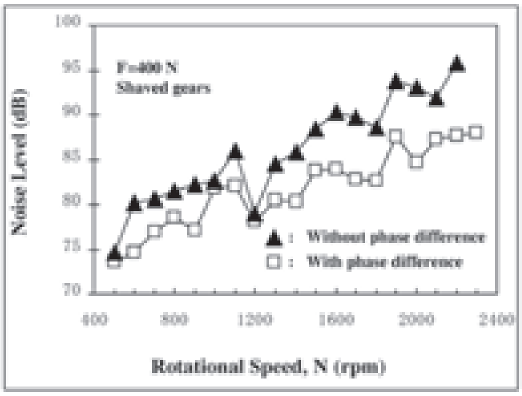


Figure 7—Effect of meshing phase difference on noise.

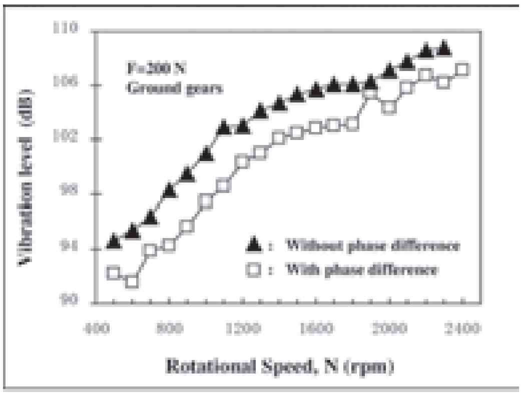


Figure 8—Effect of meshing phase difference on vibration.

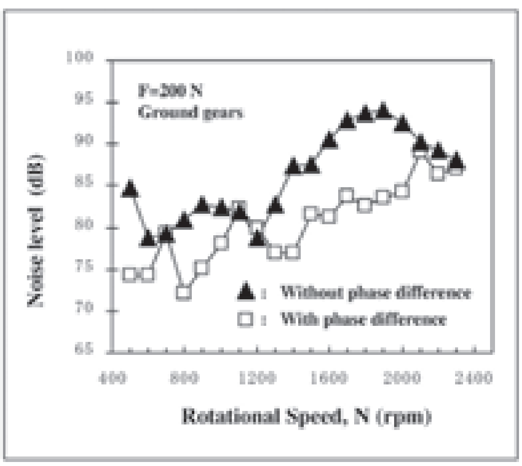


Figure 9— Effect of meshing phase difference on noise.

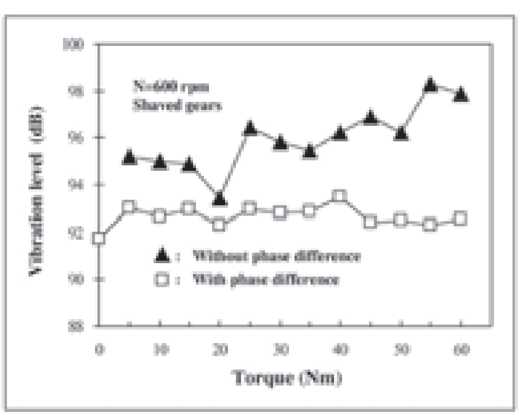


Figure 10—Effect of meshing phase difference on vibration.

set testing machine housed in a soundproof box.

Experimental Results and Discussion

Effect of meshing phase difference on vibration and noise. Figure 6 and Figure 7 show the effect of the meshing phase difference on the measured vibration and noise levels of the planetary gear sets when the gear tangential load was 400 N. Planetary gear pairs with full-depth teeth (profile contact ratio A in Table 1) were used as the test gears. The closed triangles and open squares indicate the change in the noise and vibration levels of planetary gear set I without a meshing phase difference and planetary gear set II with a meshing phase difference, respectively. As seen in the figures, the vibration and noise levels of the planetary gear set with the meshing phase difference were 3–5 dB and 5–7 dB lower, respectively, than the levels measured for the planetary gear set without the meshing phase difference.

Figure 8 and Figure 9 show the measured vibration and noise levels when planet and sun gears that have been ground on a Maag gear grinder were used in the test planetary gear sets. At nearly all of the measured speeds, the planetary gear set with the meshing phase difference shows vibration and noise levels that were approximately 3–4 dB and 6–9 dB lower, respectively, than those of the planetary gear set without a meshing phase difference. The effect of the meshing phase difference is presumed to be even more pronounced in these results because the influence of gear accuracy was relatively reduced by using ground gears.

The measured vibration level is shown in Figure 10 as a function of the load torque. Over the entire torque range from low to high, the planetary gear set without a meshing phase difference shows an increase in vibration of around 3–4 dB with an increase in load torque. However, the vibration level of the planetary gear set with the meshing phase difference was insensitive to load torque changes.

Influence of tooth profile contact ratio and accuracy on vibration and noise. Figure 11 shows the measured noise level when planet gear pairs with large and small transverse contact ratios (profile contact ratios A and B, respectively, in Table 1) were used in planetary gear sets incorporating a meshing phase difference. The noise and vibration levels for the planetary gear sets with different contact ratios (i.e., full-depth teeth vs. normal-depth teeth) did not show any clear differences.

When contact ratios differ, the cyclic change in the spring stiffness of the meshing teeth varies, so the change in meshing excitation forces that occurs due to the change in the spring stiffness of the gear pairs is cancelled out in a planetary gear set with a meshing phase difference. Therefore, the effect on the gear noise level is presumably reduced even if the contact ratio is increased by using gears with full-depth teeth, which would account for the lack of a clear difference in Figure 11.

The effect of test gear accuracy on the vibration level of planetary gear sets with a meshing phase difference is shown in Figure 12. The measured vibration levels compared here are for sun and planet gears that were shaved only and hardened by carburization and those that were ground after being hardened by carburization.

The vibration level of the planetary gear set built with the ground gears was 1–4 dB lower. This lower level is attributed to the improved machining accuracy of the gears and the reduced roughness of the tooth face. The reduced vibration was especially pronounced at rotational speeds above 1,800 rpm.

Effect of the rotational order on vibration. The vibration components were measured using a fast Fourier transform (FFT) analyzer. Figure 13 and Figure 14 show the effect of the meshing phase difference on the first- and second-order meshing components of the measured vibrations.

Among the variable components of the dynamic planetary gear set load, the first-order component generally has the largest amplitude (Ref. 4), but passenger compartment quietness (an NVH characteristic) is thought to be mainly influenced by the first- and second-order meshing vibration components of the planet gear noise of an automatic transmission. The experimental results in Figures 13 and 14 indicate that the first- and second-order vibration levels of the planetary gear set with a meshing phase difference were rather low. In other words, it has been shown experimentally here that a meshing phase difference design can reduce the first- and second-order meshing vibration components.

Vibration acceleration and noise frequency analysis. Figure 15 and Figure 16 show the measured noise levels and frequency components of the vibration acceleration of planetary gear sets with and without a meshing phase difference when sun and planet gears having ground tooth faces were used. The noise level and vibration acceleration level of the planetary gear set without the meshing phase difference were approximately 3–9 dB higher.

The first- to third-order components of the planet gear meshing frequency, fz, also show higher peaks than those seen for the planetary gear set with the meshing phase difference, which indicates that frequency components were present in the high-frequency range as well.

In the case of the planetary gear set with the meshing phase difference, the meshing phases of the teeth of the planet gears when they meshed with the sun gear had a differing composition. Consequently, the meshing phases of the torsional vibrations induced by changes in the spring stiffness of the teeth accompanying changes in the meshing states of tooth pairs

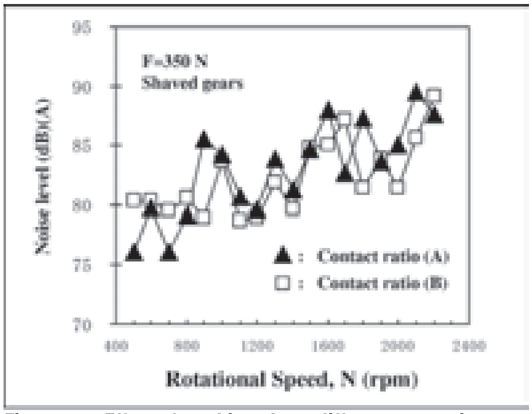


Figure 11—Effect of meshing phase difference on noise.

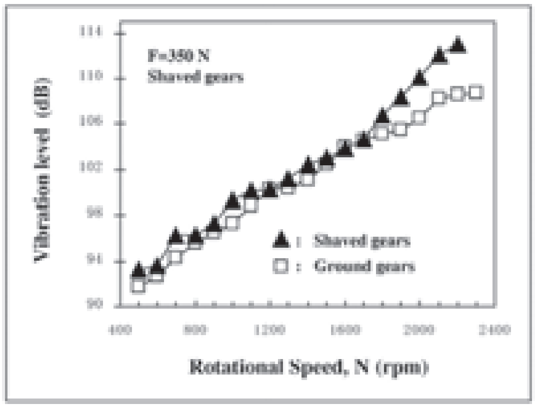


Figure 12—Effect of grinding on vibration.

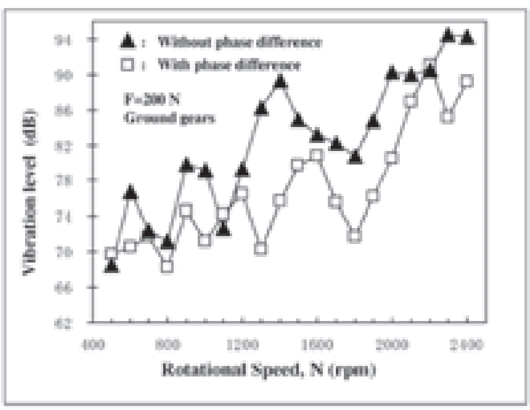


Figure 13—Effect of first-order meshing frequency of meshing phase difference on vibration.

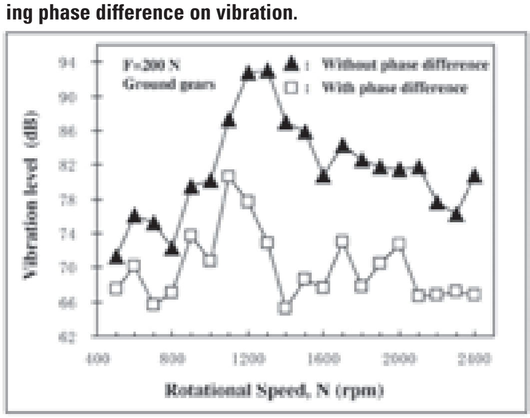


Figure 14—Effect of second-order meshing frequency of meshing phase difference on vibration.

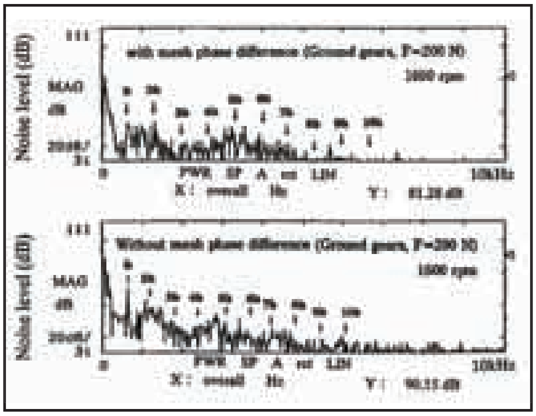


Figure 15—Noise spectrum of planetary gear sets.

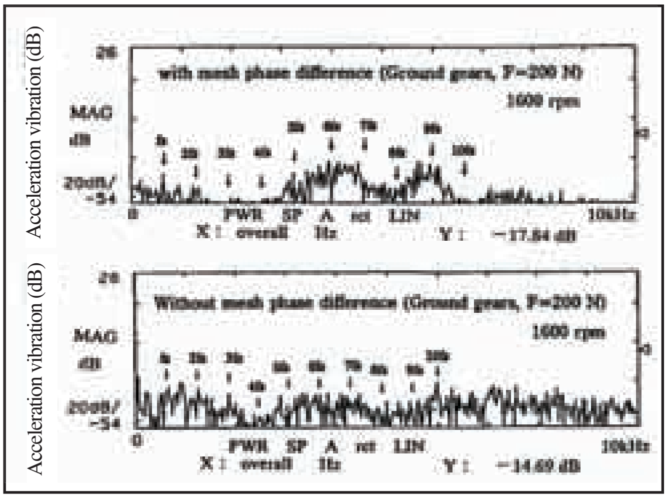


Figure 16—Acceleration spectrum of planetary gear sets.

differed in their composition. Therefore, it is assumed that the resulting interference had the effect of mitigating the noise and vibration levels of the planetary gear set with the meshing phase difference.

Measured vibration results for planet gears in vehicle tests. Figure 17 shows the first-order meshing frequency of the vibration acceleration levels measured for planet gears with and without a meshing phase difference in tests conducted with a 2.0L front-wheel-drive car fitted with a four-speed automatic transmission. Schematic diagrams of the automatic transmission used in the tests are given in Figure 4. This automatic transmission consisted of two planetary gear sets. The specifications of the planetary gear sets are given in Table 2. Measurements were made under a condition of gradual acceleration in first and fourth gears. As seen in the figure, the vibration acceleration level of planetary gear set II with a meshing phase difference was approximately 3–12 dB lower than that of planetary gear set I without a meshing phase difference. Better results were thus obtained by applying a meshing phase difference.

Conclusions

An original planetary gear set testing machine was designed and built so planetary gear sets in four-speed automatic transmissions fitted on production vehicles can be tested separately in each speed range. Planetary gear sets were tested under varying rotational speeds and tooth face loads to examine how vibration and noise were affected by different methods of finishing the test gears, different contact ratios and other factors. The results obtained are summarized below:

1.) It was shown that applying a meshing phase difference to planet gears reduced planetary gear set vibration and noise.

2.) When a phase difference was applied to the meshing of gear teeth, it was seen that the noise and vibration levels of the planetary gear set were less susceptible to the influence of the tooth profile contact ratio.

3.) It was also shown that the noise and vibration levels of a planetary gear set with a meshing phase difference can be further reduced by improving gear accuracy and tooth face roughness.

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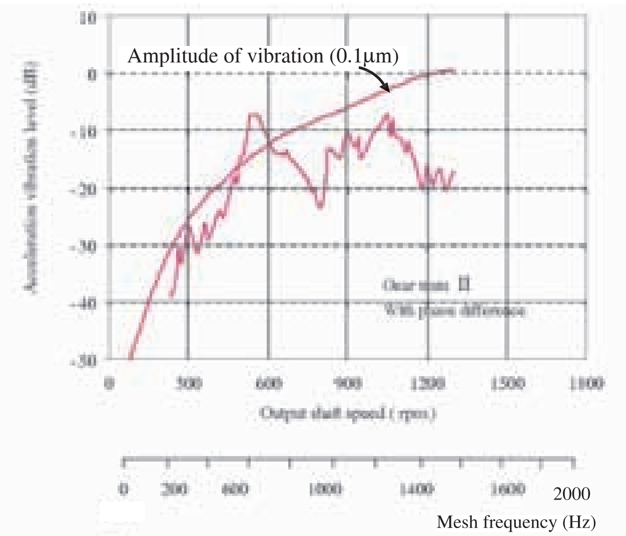
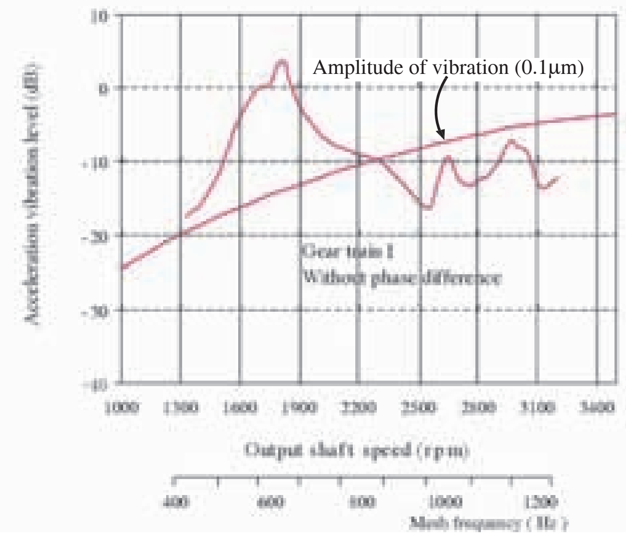


a) Measured vibration acceleration with a meshing phase difference (first-order meshing frequency, 1st)



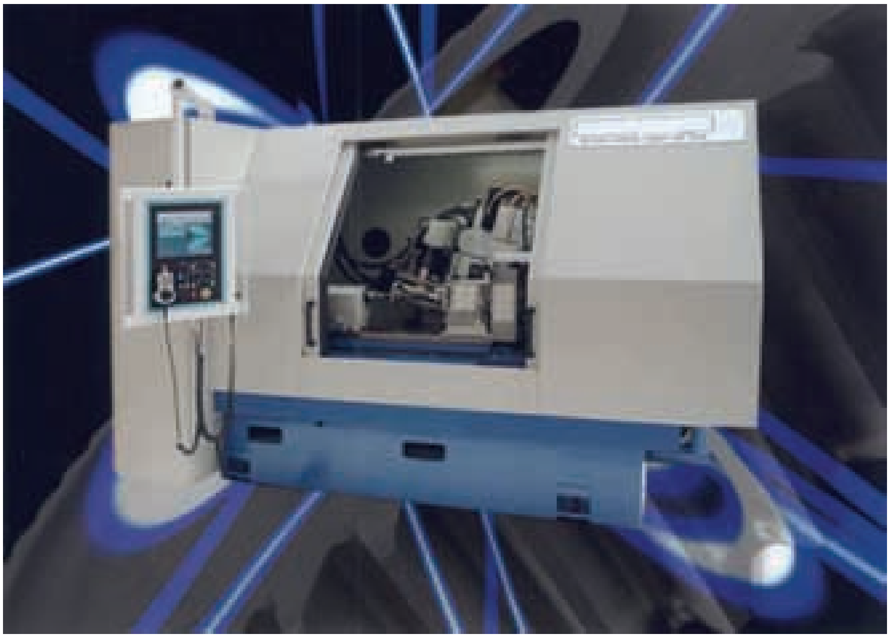
b) Measured vibration acceleration level without a meshing phase difference (first-order meshing frequency, 4th)

Figure 17—Measured vibration acceleration levels in vehicle tests.

Table 2—Specifications of Vehicle Test Planetary Gear Sets.

	Planetary gear set I			Planetary gear set II		
	Sun	Planet	Ring	Sun	Planet	Ring
Number of teeth	33	21	75	42	17	75
Module (m_n)	1.23			1.23		
Pressure angle (deg)	20º			20º		
Number of planets	3			4		
Helix angle (deg)	23.26º			23.26º		

Mitsubishi Gear Technology Adds Holroyd Machine



Mitsubishi Gear Technology Center has added the Holroyd GTG2 precision helical grinding machine to its portfolio.

Ian Shearing, vice president of sales for Mitsubishi, says, "The Holroyd GTG2 grinder is part of the missing piece of the puzzle, which will lead our product range into the hard gear finishing field. The GTG2 is not a machine or technology that we currently represent, and we believe that it offers the potential to increase our profit margins by opening doors to a wider customer base, i.e. high quality gear producers. None of the Mitsubishi machines that we sell currently are hard gear finishers."

The GTG2 is a gear grinding center developed for one-off or batch production of high precision helical, spur and worm gears in sizes up to 350 mm in diameter and face widths up to 160 mm.

Shearing says the biggest challenge is to sell the first machine in the U.S. and he hopes to sell four to six machines a year, if the economy stays at its current pace.

Kinefac Introduces Forced Thru-Feed Spline Rolling to China

Kinefac Corp. is introducing its cylindrical die spline rolling process to markets in China, India and other countries in the Far East.

Unlike the traditional rack rolling method, Kinefac's process uses three cylindrical dies arrayed around the shaft. The dies are independently driven but maintained in precise rotational phase with respect to one another by a central splined phasing plug. This in turn engages the end of the shaft on which the spline is to be formed and drives it in a conjugate relationship with respect to the dies as shown in the diagram.

Teeth are formed by the action of the forming section at the front of the die and, once formed, are maintained in the correct axial position by the balance of the die teeth. The shaft is fed axially through the dies by a hydraulic cylinder operating on the opposite end of the shaft. This results in a low radial forming force on the body of the shaft, which makes it possible to roll splines on hollow parts. In addition, because of the feed-thru nature of the process, the three-cylindrical-die machine can also roll much longer splines.

President, Vice President Appointed at Bison Gear

Larry Kujovich was hired as president of Bison Gear & Engineering, and George Thomas was promoted to executive vice president.

Kujovich previously held the positions of president at Chesire Co. (a Xerox company) and Xerox Medical Systems and of divisional vice president of The Toro Co. Additionally, he was president and CEO of Dietzgen Corp. and eventually became the owner. His areas of expertise include top line growth, brand and market development, technology integration and distribution channel management.

George Thomas has been with Bison Gear since 1983. He started as an applications engineer and was later promoted to product manager and facilitated company-wide total quality management programs and lean operation initiatives. Thomas was named vice president of engineering in 1993, vice president of operations in 1996 and senior vice president in 2004.

Ronald D. Bullock will continue to serve as chairman and CEO. Bullock has been with Bison Gear since 1981 and acquired the company in 1987.

Bodine Appoints New Vice President

Bodine Electric Co. hired Wes Hawkins as vice president of manufacturing. Among his new responsibilities will be continuing to implement lean manufacturing efforts.

Hawkins was previously in charge of manufacturing, logistics and product management at Schneider Electric/ Square D.

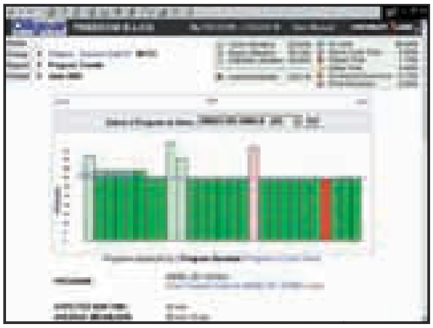
In addition, Bodine also hired two new area sales managers. Dan Orr will be responsible for sales in Florida, Alabama, Georgia, Louisiana and Texas. Over the past 20 years, Orr has worked at Emerson, A.O. Smith and Fasco in motor applications and OEM sales. Johnny Persson was hired as area sales manager for Scandinavia and the Baltic States.

Schafer Manager Returns from Afghanistan

Major Robert Doshi has returned to his position as production manager at Schafer Gear Works.

For the past year, Doshi has served in the U.S. Army in various locations in Afghanistan. While in Afghanistan, Doshi worked as a trainer for the new Afghanistan national army.

Cincinnati Machine Launches Second Phase of Smart Machine Initative



Cincinnati Machine has been awarded $2.4 million by the National Center for Manufacturing Sciences to fund the second phase of its Smart Machine manufacturing technology initative. During this phase, the company will provide overall project coordination and lead the deployment of technology at partner sites.

According to the company's press release, the Smart Machine initiative is a collaborative effort between several commercial firms, government agencies and military facilities to demonstrate the viability of functional Smart Machine concepts on a variety of machine tools and special process equipment. Machines at partner sites will be equipped with monitoring capability to automatically gather and report performance status. Autonomous software monitoring of data identifies anomalies and reports potential problems.

In the Smart Machine pilot project, the partner companies collaborated with Red River Army Depot and Cherry Point Naval Depot in implementing four proof-of-concept "Smart Machine" installations focused on maintenance support functions. The project defined specific achievable objectives for the subsequent Phase II project that could lead towards a more advanced Next Generation Factory. Among the benefits noted in Phase I were a reduction in manufacturing process variation in a rubber compression molding application and an improvement in process efficiency of a diesel engine transfer line.

The Smart Machine Phase II will expand on the pilot project's original four sites to nine depot and industrial partner sites, culminating in September 2006. Additional objectives include providing secure management access to the shop floor data produced by the installations.

American Wera Establishes New Program

American Wera has initiated a new service with its German-based parent company, WERA Works Wuppertal, to support customers in setting up new manufacturing lines or production plants.

United States Postal Service

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PS Form **3526,** October 1999 *(See Instructions on Reverse)*

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d. Free Distribution by Mail *(Samples, compliment ary, and other free)* (1) Outside-County as Stated on Form 3541	1,615	1,236
(2) In-County as Stated on Form 3541	–	–
(3) Other Classes Mailed Through the USPS	–	–
e. Free Distribution Outside the Mail *(Carriers or other means)*	1,419	2,133
f. Total Free Distribution *(Sum of 15d. and 15e.)*	3,034	3,369
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Michael Goldstein, Publisher Date **10/07/05**

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3. Be sure to furnish all circulation information called for in item 15. Free circulation must be shown in items 15d, e, and f.
4. Item 15h., Copies not Distributed, must include (1) newsstand copies originally stated on Form 3541, and returned to the publisher, (2) estimated returns from news agents, and (3), copies for office use, leftovers, spoiled, and all other copies not distributed.
5. If the publication had Periodicals authorization as a general or requester publication, this Statement of Ownership, Management, and Circulation must be published; it must be printed in any issue in October or, if the publication is not published during October, the first issue printed after October.
6. In item 16, indicate the date of the issue in which this Statement of Ownership will be published.
7. Item 17 must be signed.

Failure to file or publish a statement of ownership may lead to suspension of Periodicals authorization.

PS Form **3526,** October 1999 *(Reverse)*

According to American Wera's press release, the company is currently under contract for such services with a major automotive supplier.

The program focuses on writing specifications, requesting quotes, adhering to health and safety regulations, fulfilling contracts, following up and obtaining machine acceptance. American Wera aims to unburden technical personnel, achieve on-target timing, and lower capital costs.

Applied Process Hires New Plant Manager


Steve Sumner

Steve Sumner was appointed plant manager at Applied Process of Livonia, MI.

Sumner is a metallurgical engineer with 18 years of experience in his prior roles as R&D technician, ISO/QS management representative, factory set-up engineer and plant manager. He is currently pursuing a graduate degree in industrial management.

Sumner will report to John Wagner, chief operating officer at Applied Process.

Fiberfil Acquires Business Unit of DSM Plastics

Fiberfil Engineered Plastics acquired the North American custom compounding unit of DSM Engineering Plastics, effective Dec. 7.

Fiberfil acquired the company's North American polypropylene business in conjunction with the manufacturing site in Stoney Creek, Ontario, Canada. At this site, Fiberfil Engineered Plastics operates under the company name Fiberfil Engineered Plastics and will continue to operate under the Fiberfil trademark.

The new company will focus on the development and growth of the new and existing polypropylene business.

Inductoheat Hires New Sales Manager

Gerald Wills was hired as Inductoheat's district sales manager for Ohio and western Michigan, Kentucky, Pennsylvania and West Virginia.

Wills has worked at Inductoheat since May 2005.

Send your news items to Robin Wright via email to *robin@geartechnology.com*

Winter 2006—Induction Heating Training. This course is held at the customer's facility or at Inductoheat's Madison Heights, MI, facility. The course focuses on metallurgy and heat treating principles, specifics of induction heating applications, power supply load matching, electromagnetics, thermal processes and mathematical modeling and computer maintenance. Basic, intermediate and advanced level courses are offered. The on-site training charge is the current service rate (about $1,200 per day) for onsite training. Training at the Inductoheat facility is free, and the next scheduled training is September 15–16, 2006. For more information, contact Inductoheat by telephone at (800) 624-6297 or on the Internet at *www.inductoheat.com*.

March 7–9—Expo Manufactura. Cintermex, Monterrey, Mexico. Mexico's leading machine tool and metalworking expo. Technology is separated into machine tools, CAD/CAM and software, quality manufacturing, fabricating and forming, lasers, automation and controls, assembly equipment, electronic manufacturing, robotics and welding. Registration is free and takes place on-site. For more information, contact E.J. Krause & Associates by telephone at (301) 493-5500.

March 7–10—Metal Gear Design and Manufacturing. UTS facility, Rockford, IL. This class begins with basic gear theory and proceeds through such advanced topics as minimum weight design strategies, gear size, geometry design, rating, producibility analysis, torsional analysis, gear noise, lubrication and profile analysis. Also introduces concepts of tool design and tooling selection. $1,250. Participants can also register for TK Solver training on March 6 for an additional $295. For more information, contact UTS by e-mail at *sales@uts.com*.

March 27–30—WESTEC 2006 Expo and Conference. Los Angeles Convention Center, Los Angeles, CA. Sponsored by the Society of Manufacturing Engineers, this event showcases the latest automation and assembly solutions for the aerospace, automotive, biotechnology, chemical, computer, cosmetics, defense and electronics industries. Registration is free until March 10, 2006. After that time, registration is $50. For more information, visit the Society of Manufacturing Engineers on the Internet at *www.sme.org*.

April 5–7—Detailed Gear Design: Beyond the Simple Service Factors. Flamingo Hotel, Las Vegas, NV. An intensive seminar to help designers understand gear rating and analysis factors, ISO/AGMA analysis methods, differences in stress states, optimization of gear tooth design parameters and much more. Seminar is run by Ray Drago. Prices range from $1,195–$1,895. For more information, contact the American Gear Manufacturers Association by telephone at (703) 684-0211 or on the Internet at *www.agma.org*.

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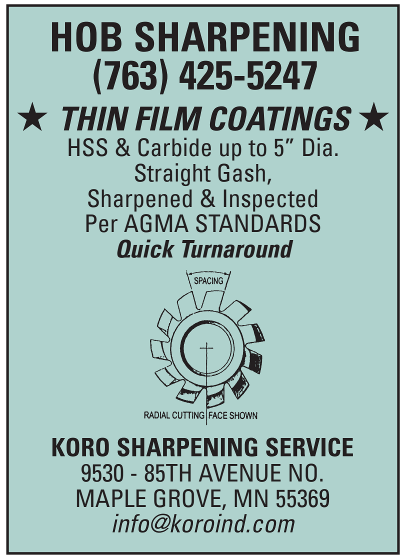

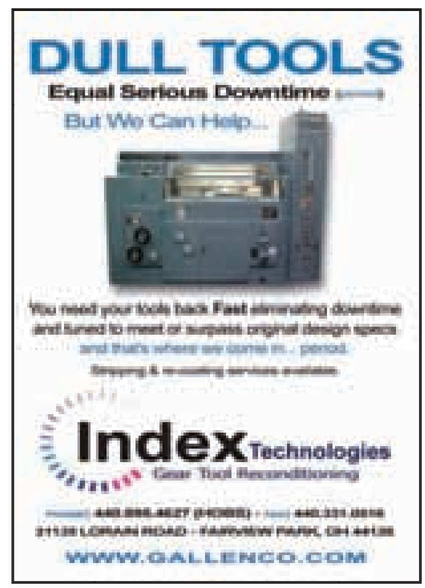

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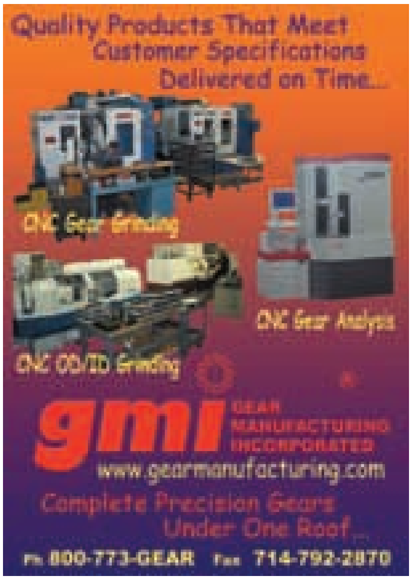

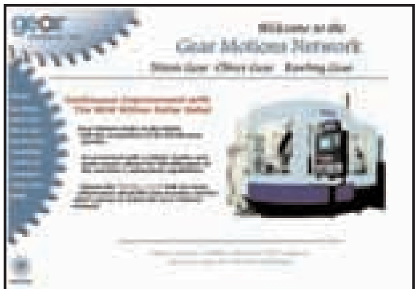

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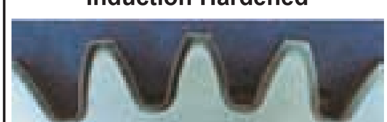

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Wicked Gears

Photo by Joan Marcus.

It's not often that thespians and engineers find common ground, but the hit musical *Wicked* could provide conversational tidbits for right and left-brainers alike.

Wicked is the story of the witches of Oz *before* they met Dorothy. Central to the plotline is the friendship between The Wicked Witch and Glenda the Good Witch. But any theatre reviewer can tell you that much. Only the Addendum team can cut to the chase fast enough to tell you the *real* reason to invest at least $30 ($50 in New York) and two hours and forty minutes of time….The entire backdrop of the show is GEARS!

We kid you not. These gears don't transmit mechanical power or perform any other activity that takes place in a gearbox, but they work well as artistic elements.

Even better, *Wicked* is slated to run through the spring of 2007 in major cities throughout the U.S. and Canada with more return engagements possible—taking care of chitchat for at least one more round of holiday parties.

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