The Applications of Bevel Gears

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EDITORS' NOTE: *"The Applications of Bevel Gears" is the excerpted third chapter of Dr. Hermann Stadtfeld's latest book*—Gleason Bevel Gear Technology *(The Gleason Works, Rochester, New York, USA; All rights reserved. 2014; ISBN 978-0-615-96492-8.), which appears here unabridged through the kind graces of Dr. Stadtfeld and Gleason Corp. Future installments will appear exclusively in* Power Transmission Engineering *and* Gear Technology *magazine over the next 12 to 18 months.*

A Word From the Author

Much has occurred in our industry over the past 10 to 15 years. A singular example is the heightened complexity—and opportunity—that now exists in making "best choices" for optimal transmission elements.

Indeed—21st Century gear technology not only offers methods for the calculation and manufacture of classical bevel and hypoid gears; it also now presents a variety of possibilities for the three-dimensional transmission of power via gear types that—once-upon-a-time—could only be manufactured on special machines with exotic, expensive tools.

This book was written and is intended for specialists in Planning, Engineering, Gear Design and Manufacturing. It also serves to help meet the technical information needs of those researchers, scientists and students who deal with the theory and practice of bevel gears and other angular gear systems on a regular basis.

What's more, Gleason Bevel Gear Technology *is the first multi-translated textbook available worldwide that goes beyond explicating the abovementioned methods. It also imparts practical suggestions for their application.*

The basics-oriented, introductory chapters of this book guide both engineers and students with no gear experience in an easy, reader-friendly way through the basics of modern cylindrical and bevel gear technology. A vector math is introduced that enables every gear specialist to create an Excel *spreadsheet and conduct their own experiments in order to gain a better understanding of the complex bevel gear geometry.*

It must be noted and acknowledged that The Gear Praxis*—published by Karl Friedrich Keck in 1958—is the inspiration for this book; it describes, in comprehensive detail, bevel gear technology from a mid-20th-Century perspective. Indeed,* The Gear Praxis *in turn inspired me to write this book, addressing all aspects of the state of actual bevel gear technology—but with an early* 21st Century *perspective.*

Introduction

An introduction to gear theory and the fundamental, gear-mathematical explanations required to understand the geometry of bevel gears has been provided in the preceding chapters. Thus informed, Chapter 3 will introduce examples of everyday applications in the industry that serve to establish the basis for the practical-oriented chapters to come. Similar to cylindrical gears—used to reduce the RPM of a prime mover and to bridge the distance between gear shafts (parallel axes)—bevel gears are also used to reduce input RPM and to transmit motion between two axes that include an angle which can be not just 90°. This physical property of bevel gears allows the orientation between input and output shaft to be under almost any angle. The results translate to design solutions for industrial gear boxes, vehicles and aircrafts which are—due to their use of bevel gears—less complex and best-performing in their function.

Automotive

Luxury-market automobiles have optimal traction due to sophisticated weight distribution design and a "pushing"—rather than "pulling"—propulsion. A longitudinally installed engine drives via manual or automatic transmission a propeller shaft whose rotation is re-directed in the direction of the driving rear wheels by a bevel gearset with pinion shaft offset; i.e.—a hypoid gearset. In addition to enhanced

Figure 1 Rear-axle-drive of a passenger car (Source: Daimler AG).

Figure 2 Shows a luxury vehicle with longitudinally oriented combustion engine and a driven rear axle. This concept is used by all automobile manufacturers worldwide on luxury-class vehicles that feature one driven axle.

weight distribution and ideal vehicle handling, the common, disturbing tilt motion and "torque steer" — as in cases of fast gas pedal actuation — are eliminated. While it is more cost-effective to manufacture front-wheel-drive vehicles with "east/west-oriented" engines, these vehicles present for the operator a combination of disadvantages which include, along with handling, higher fuel consumption.

The cross-section of a typical passenger car rear-axle drive unit is shown in Figure 1. The input shaft offset positions the pinion below the ring gear axis; the input is on the right side and comes from the propeller shaft. Both flanges in front of and behind the ring gear will be connected to the rear wheels with driveshafts. The differential carrier with four straight bevel gears is located inside the ring gear. The two differential gears, which are on the ring gear axis, are rigidly connected to the drive flanges. The two radially oriented differential gears are connected with center pins to the differential carrier on which the ring is rigidly bolted. This configuration enables different RPM of the two driving wheels — while the vehicle is negotiating curves, for example — where the wheel towards the inside of the curve requires a lower number of revolutions than the outside wheel. (Fig. 2 shows a luxury-class vehicle with a longitudinally oriented combustion engine and driven rear axle. This concept is used by automobile manufacturers worldwide on luxury-class vehicles that feature one driven axle.)

Maximum traction is achieved in every vehicle if all wheels are driven; i.e. — all-wheel-drive (AWD) automobiles. Figure 3 shows the drive units of a vehicle with a longitudinally oriented engine and a transmission with a propeller shaft connection to the rear axle. In addition, a transfer case is mounted to the transmission exit that transfers rotation from the transmission exit to the front axle drive. Typically, transfer cases feature mechanical and electromechanical components that allow for differences in RPM and load between the front and rear axle. This is required in order to accommodate a variance in slippage between front and rear axle without winding up the geartrain, as well as the transmission of different torques to the front and rear axle. Eighty percent of the bevel gears in passenger cars are ground, while the remaining 20% are lapped.

Light and Heavy Trucks

Starting with light trucks, those with one-ton payloads are usually driven by one rear axle — with one bevel gearset in each axle unit. For both light *and* heavy trucks, the propulsion via the rear axle is considered the standard solution, while all-wheel-drive solutions are optionally available. Commercial trucks use rigid-beam-style axles, where the central transmission housing is welded to the axle tubes. The beam-style axles carry the brake mechanism in the wheel area and are connected to the truck frame with control arms. The driveshafts and their bearings are located within the axle tubes. The driveshafts have at their end, where they protrude beyond the tubes, flanges with the wheel interface. This simple design — as it is applied to trucks — shows no disadvantages. To the contrary, it is a solution that even offers good off-road capabilities.

Figure 4 shows a pick-up truck with 2.5-ton payload and a rigid-driven rear axle; the vehicle in Figure 5 is an AWD sport

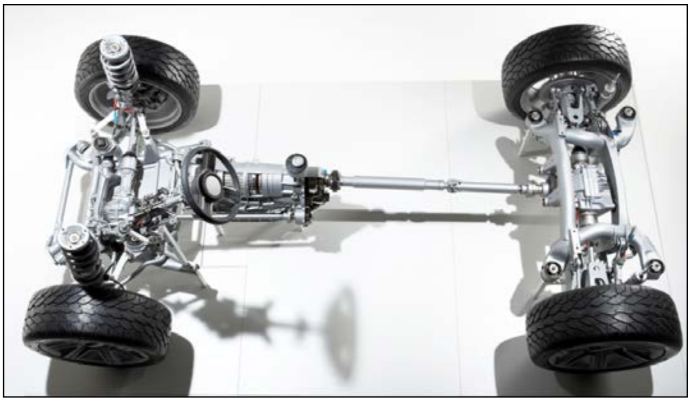

Figure 3 Drive components of a vehicle with all-wheel drive (Source: ZF Friedrichshafen AG).

Figure 4 Light truck (Source: General Motors Corporation).

Figure 5 Sport Utility Vehicle (Source: Chrysler Group LLC).

Figure 6 Class 8 semi-truck, tractor with tandem axle.

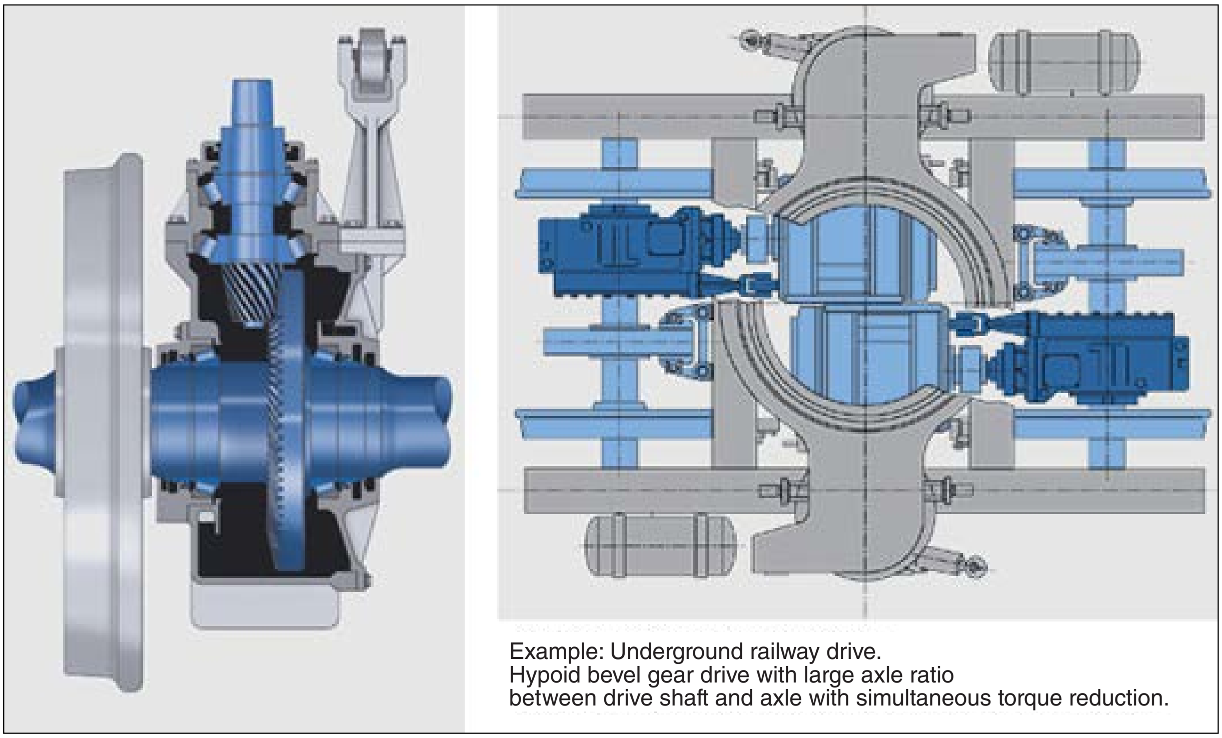

Figure 7 Drive components of a driven subway car.

Figure 8 Backhoe.

Figure 9 Excavator and scraper (Source: Liebherr).

utility vehicle (SUV). Of additional interest is that even this mixture between light truck and station wagon is mostly equipped with a beam-style rear axle, and a driven, beam-style steering axle in the front.

The tractor of the Class 8 semi-truck in Figure 6 has under the trailer pivot a driven- tandem axle; the tandem axle consists of two independent, frame-connected, beam-style axles. The first is connected to the transmission and engine with a propeller shaft, while the second axle is connected with a short propeller shaft to a transfer case located in the housing of the first axle. The transfer case has a fixed ratio that precludes slippage between the axles.

Eighty percent of the bevel gears in commercial trucks are lapped after heat treatment as a hard finishing process, while 20% are ground.

Railroad Drives

Railroad engines powered with electric motors or diesel engines feature large, longitudinally oriented prime movers whose rotation and torque are transmitted to the wheel axles with driveshafts and bevel gear transmissions.

With trolleys, subway cars or commuter trains, smaller individual, electric motors are dedicated to each axle. Also, the longitudinal motor orientation is preferred and a redirection of the motion is realized by bevel gear transmissions (Fig. 7). The bevel gearsets are ground or skived after heat treatment.

Construction Equipment

Earth-moving equipment uses bevel gears for auxiliary purposes, as well as for their propulsion. The backhoe shown in Figure 8 is very similar to a farm tractor in its basic design concept. Backhoes feature a driven, beam-style rear axle with a spiral bevel gearset (no hypoid offset). Engine, shift transmission and axle drive are connected in these tractors to one solid unit.

The excavator in Figure 9 (top) has four driven, dual wheels. Engine and transmission are located in the upper-rotatable operator cabin. The propulsion of the wheels is produced from the transmission via a bevel gearset to a vertical shaft through the center of the cabin pivot point; it is then redirected beneath the suspension frame with a second bevel gearset in the horizontal length direction. Two propeller shafts transmit the drive motion to each of the front and rear beam axles. The two beam axles also include bevel gearsets for the motion redirection to the wheel axles.

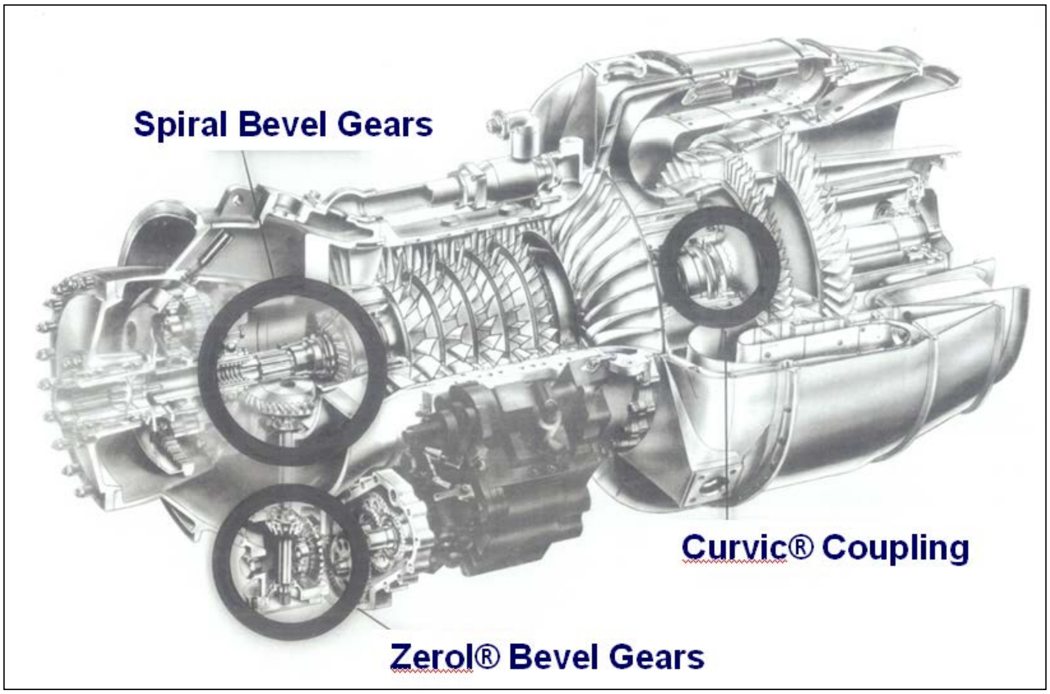

Figure 10 **Jet engine with various bevel gear applications.**

Modern scrapers, i.e. — bulldozers (Fig. 9, bottom) — apply hydrostatic-powered track chains; bevel gears are used only for the actuation of auxiliary units. Bevel gears in construction equipment are — depending upon their manufacture — either lapped, ground, skived or built — without any hard finishing operation after heat treatment.

Aviation

Jet airplane engines have all moving engine parts oriented around the main shaft. The connection of the turbine rotors is established with Curvic couplings. Auxiliary units require a power take-off from the main shaft, which is accomplished via bevel gear transmissions (Fig. 10).

Helicopters use internal combustion, or jet, engines. Modern jet engines for airplanes are designed as a turbofan, where the rotational power of the main shaft — which is generated behind the combustion chambers — is partially used to compress the air that flows into the combustion chambers, and partially to rotate one or several fans. This generates additional thrust to the thrust already generated at the engine exit. Helicopters for civil applications generate lift and thrust forces solely with the main rotor, which is why helicopter jet engines are designed to deliver all output energy on the main shaft, which in turn is used to power the main rotor instead of a turbofan. In both cases, piston or jet engine, there is a necessary redirection of the rotation from the near-horizontally oriented output shafts to the vertical direction of the main rotor axis.

The high, maximal RPM of 18,000 in cases of one or two turbines is reduced with a first bevel gearset by a factor of three, and further reduced by a factor of four-to-eight with the main rotor drive. The main rotor drive has a large ring gear — 80 to 120 teeth — that is driven by one or two pinions (depending on the number of engines). Additional pinions are grouped around the circumference of the ring gear that take off redirect and power to auxiliary units such as a hydraulic pump and electrical generator. Also, energy for the tail rotor is branched off the main rotor ring gear by an additional pinion. At the tail rotor, another bevel gearset is utilized in order to redirect the rotation of the driveshaft running through the helicopter tail into the direction of the tail rotor axis.

Figure 11 **Helicopter with bevel gear actuated main and tail rotor (Source: Agusta Westland a FINMECCANICA Company).**

Helicopter transmissions total about 10 bevel pinions and four ring gears — some of which have, for example, a hypoid offset in order to account for the asymmetric orientation of the tail rotor and its driveshaft. Because of space constraints and tight component packaging, almost all bevel gearsets are realized with shaft angles less than 90°. Helicopter transmissions are the most sophisticated and complex application for bevel gear systems. All aerospace power transmissions require ground flank surfaces and ground root fillets after heat treatment (Fig. 11).

Figure 12 Industrial gearboxes with different size.

Figure 13 Stern drive with two propellers (Dual-Prop) (Source: Konrad Marine).

Industrial Gearboxes

Industrial gearboxes are used in machines and equipment across many different industries. Redirection of motion is as often required as the reduction of RPM between parallel axes. A typical industrial gearbox similar in appearance to what is used to actuate escalators, assembly line belts, lifting devices, and special machines is shown (Fig. 12, left). The efficiency of these gearboxes becomes increasingly important, as many of them have a 24/7 duty cycle. Industrial gearboxes are available with ring gear diameters ranging from below 50 mm up to diameters of 2,000 mm — due to their many different industrial applications. In Figure 12 (right) an angular transmission that drives a larger pump with a ring gear diameter of 1,000 mm is shown. Industrial gearboxes are hard-finished with skiving or grinding after their heat treatment.

Marine Transmissions

Stern drives (more commonly known as "outboard motors") require two bevel gearsets between the motor and propeller. The high-power unit (Fig. 13) has two opposite hand propellers that rotate in opposite directions (twin-prop). The drivetrain of this unit is equipped with CONIFLEX straight bevel gears that are not hard-finished after heat treatment. Straight bevel gears — with optimized root fillet and a strength-increasing shot peening treatment — show for this particular application a higher root bending strength than spiral bevel gears.

Oceangoing vessels with a central, inboard motor utilize bevel gears to run the propeller shafts with changing angles along the hull to the ship's stern. A power split onto two stern propellers — typical in many large ships — is handled by bevel gearsets with low shaft angles between 5° and 20°.

Thrusters (Fig. 14) have been used for many decades in ocean exploration platforms such as those used for pumping crude oil. On each of the four corners of such platforms a thruster with a propeller diameter of several meters is attached. The thrusters are used to maneuver the platform from shore to its geographical ocean location; once at the service location, they help maintain platform stability.

A thruster's base construction is reminiscent of a gigantic stern drive. Today's smaller-size thrusters are used to propel ships; they afford excellent maneuverability — which is why they are used in pilot boats and ice breakers, as well as in ships requiring nimble harbor maneuverability. Thrusters can also be attached to a vessel as a module; this eases or eliminates many of the existing restrictions in ship design that can be traced to the conventional "inboard" drivetrain and its location of the motors and propeller shafts.

Thrusters use two bevel gearsets (Fig. 14); depending on the application, the ring gear diameters can vary between 600 mm and 2,500 mm. Ninety percent of the bevel gears for the propulsion of ships are skived, while 10% are ground as a hard finishing operation.

Special Applications

Large bevel gears—not hard-finished after heat treatment—are found in equipment and machines for the surface mining of coal and ore (fracking), as well as for stone crushing and stone mills. In some cases these large bevel gears are assembled without any post-cutting heat treatment; in others, a flame or induction hardening is performed. Figure 15 shows an oil drilling platform; the rotation of a horizontally oriented, internal combustion engine is re-directed in the orientation of the drilling rod. This application requires the transmission of high torque with rotary impulses generated by the stone-drilling action and the elasticity of the long rod. The bevel gearset must have a high degree of toughness in order to avoid tooth fracture due to, for example, a locking drill. To fulfill the requirements above, the bevel gears are surface-hardened and, because there is a ring gear diameter of about 1,500 mm in this unit, the bevel gears are hard-finished by skiving, as grinding is usually only recommended for diameters of up to 800 mm. **PTE**

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Figure 14 Thruster for marine applications (Source: Rolls Royce Marine).

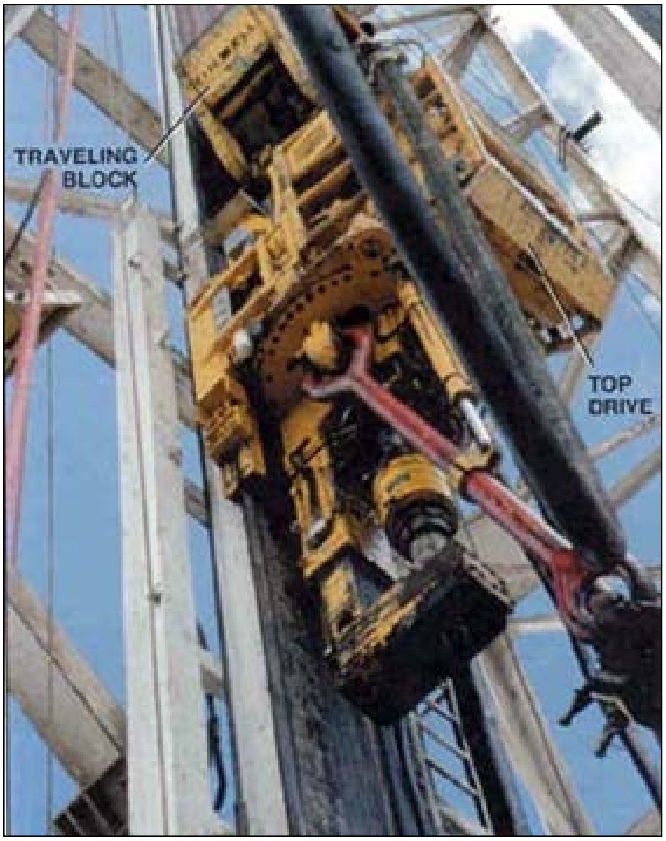

Figure 15 Oil drilling tower.

Dr. Hermann J. Stadtfeld received in 1978 his B.S. and in 1982 his M.S. in mechanical engineering at the Technical University in Aachen, Germany; upon receiving his Doctorate, he remained as a research scientist at the University's Machine Tool Laboratory. In 1987, he accepted the position of head of engineering and R&D of the Bevel Gear Machine Tool Division of Oerlikon Buehrle AG in Zurich and, in 1992, returned to academia as visiting professor at the Rochester Institute of Technology. Dr. Stadtfeld returned to the commercial workplace in 1994—joining The Gleason Works—also in Rochester—first as director of R&D, and, in 1996, as vice president R&D. During a three-year hiatus (2002-2005) from Gleason, he established a gear research company in Germany while simultaneously accepting a professorship to teach gear technology courses at the University of Ilmenau. Stadtfeld subsequently returned to the Gleason Corporation in 2005, where he currently holds the position of vice president, bevel gear technology and R&D. A prolific author (and frequent contributor to Gear Technology), Dr. Stadtfeld has published more than 200 technical papers and 10 books on bevel gear technology; he also controls more than 50 international patents. on gear design, gear process, tools and machinery.