

Simulation of Spiral Bevel Gear Tooth Manufacturing to Aid in One-Piece Gear Shaft Design

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Introduction

Many spiral bevel gear applications are implemented with a two-piece gear where the gear and shaft are bolted or inertia-welded as an assembly task. Eliminating a bolted, splined, or welded joint between the spiral bevel gear and shaft can reduce complexity and cost in a transmission design. Simulations of the motion of spiral bevel machine tools have been developed to ensure successful integral shaft designs for helicopters. Awareness of the location of the wheel during spiral bevel gear tooth manufacturing enables a design solution to iterate between the gear shaft and spiral bevel gear tooth design. The simulation was revisited to refine a preliminary two-dimensional tool as well as create a more detailed three-dimensional visualization for use during the design process. The design process was applied to three helicopter bevel gear designs. Physical verification was completed on two designs as a risk reduction in the bevel gear grinding machine before the design was released to manufacturing. The tools used in the design process, as well as verification during manufacturing, are discussed in this publication for three different integral shaft spiral bevel gears for helicopters.

In helicopter applications, spiral bevel gears are used to transfer power and reduce speed from engines to rotors. In order to attain the best performance for helicopters, there is a desire to design a small gearset on stiff shafts supported on bearings in a straddle mount arrangement. A straddle mount arrangement is a shaft design where support bearings are mounted on either side of the gear head. Contrarily, an overhung mount arrangement is where the gear head is at the end of the shaft and the bearings are arranged behind, resulting in a typically less stiff arrangement. If a stiff, straddle mounted support is desired, the gear head and shaft must be designed so that the shaft does not interfere with the cutting and grinding of the spiral bevel gear teeth. In many spiral bevel gear designs, a straddle-mounted gear and shaft are joined after spiral bevel gear tooth cutting and grinding.

In helicopter applications, the two-piece gear is typically joined by welding, bolts, or splines. The tolerances that control the alignment of the shaft to gear head needed for light-weight, high-torque gearing pose a challenging weld manufacturing problem. Welding late in the manufacturing process yields high scrap costs since the majority of the manufacturing has been invested prior to the weld operation. Although very common in the general gear industry, bolted joints can be problematic when applied to helicopters where high reliability is desired. Work has been done to reduce fretting and corrosion in these

joints, which can result in crack initiation and torque transfer failure if not detected. In the case of the U.S. Army CH-47D Chinook helicopter, a decision was made to eliminate these joints through the use of integral design (Ref. 1). Integral shaft spiral bevel gears must be designed such that the shaft does not interfere with gear tooth cutting and grinding. This paper discusses techniques that have been updated from those presented in Reference 1 to further iterate in the design stage before manufacturing begins. Techniques described were applied to the development of integral shaft designs for a growth project for the CH-47 Chinook and two designs for a new transmission for the SB>1 DEFIANT aircraft for the Joint Multi-Role Technology Demonstrator (JMR TD) Program. Figure 1 shows an integral shaft straddle mount gear and mating overhung mount pinion.



Figure 1 Integral shaft, straddle mount spiral bevel gear and mating overhung pinion.

Preliminary Design

In each of the three integral gear shaft designs, the goal is executing the lightest producible design that meets strength and stiffness design requirements. The gear shaft design process is the same as other design processes, where compromise is the solution. The gear shaft was required to have a large diameter for an integral clutch mounted in the inner diameter in one case and an internal spline in another. A third design consisted of an existing shaft design in which a new spiral bevel gear design was developed. All three designs are straddle mount gear arrangements.

The spiral bevel gear mesh is sized first for durability and strength. The motion of the spiral bevel gear tooth machine is then overlaid to view space available for a shaft design. Both the machine tools that cut the initial gear teeth and the grinding wheel that grinds the gear teeth follow a similar path. Consideration of one or both depends on the envisioned manufacturing process. Capability has improved to the extent that gear tooth grinding machines can be used to grind gear teeth from solid instead of relying on dedicated cutting machines. This allows for less tooling and shorter schedules in fast-paced, low-quantity spiral bevel gear projects. In this case, only the grinding process was considered for the SB>1 DEFIANT aircraft while the CH-47 Chinook gear utilized both cutting and grinding.

The Gleason Works maintains a cutter path plot program that plots the tips of the cutter blades or another point of interest, such as cutter bolt heads of the machine for face milled designs. The program rotates points of interest from the cutter head onto the gear reference frame and plots the distance of each point to the gear axis in two dimensions. Three positions are plotted — one where the machine is at the toe end of the gear tooth; one where the middle of the tooth is in contact; and one where machine is at the heel end. In gear terminology this motion is referred to as “toe,” “mean,” and “heel roll” positions. The roll positions — defined as a roll angles — are specific positions of the resulting synchronized motion of the cutter head and part during the gear tooth cutting or grinding process (Ref. 2). The program requires the basic parameters of the spiral bevel gear design to be completed in order to draw a path of the point of interest. Points can be exported to overlay on the shaft cross-section in a general computer-aided design (CAD) package. Figure 2 shows an example of a two-dimensional plot overlaid onto a cross-section of the integral shaft gear.

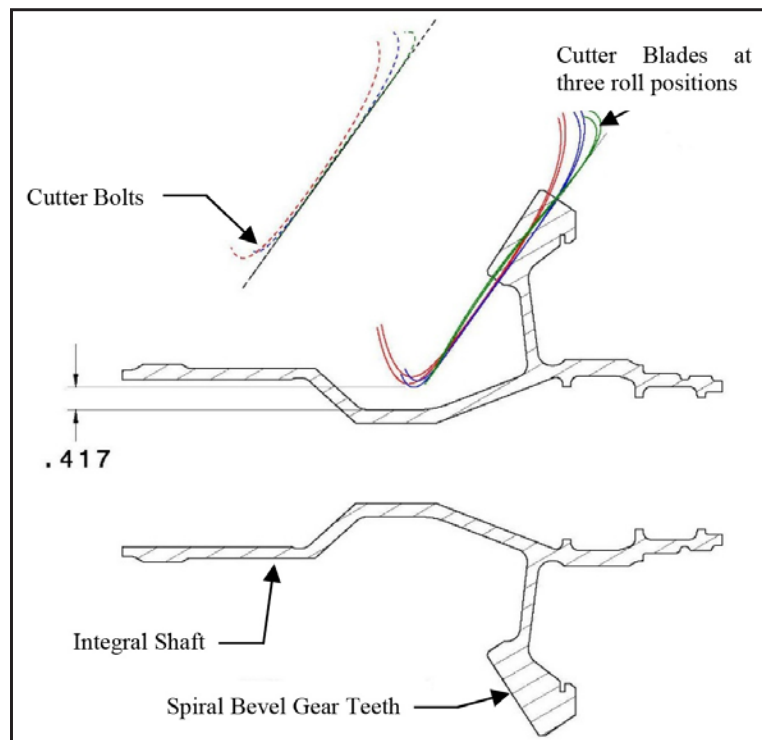


Figure 2 The Gleason Works two-dimensional cutter path plot overlaid onto a cross-section of an integral shaft gear.

At this stage of the design we are primarily interested in the smallest diameter shaft that is clear of the cutter blade tips. In order to speed the cycle time of the process, an inclusive program with fewer inputs was desired that would plot the cutter paths in a two-dimensional shaft reference frame, as well as a shaft diameter of interest to rough in a compromise between the shaft and spiral bevel gear tooth designs. Solutions were iterated between the gear tooth design and the shaft design until the smallest solution gear head with a cutter path design that cleared the shaft by a minimum of .060 inch (1.5 millimeters) was found. Once found, other gear shaft features were located to clear the cutter blade tips and bolts.

Preliminary Two-Dimensional Cutter Path Tool

Reference 1 describes a FORTRAN-written tool for drawing the cutter path of a spiral bevel gear design in a two-dimensional coordinate system. The design tool was recreated by applying descriptions detailed by Litvin and Lee (Ref. 2) to a program written in the MATLAB software application by The MathWorks, Inc.

The preliminary design tool calculates the path of a point on the cutting tool relative to the axis of the gear shaft. Typically, the path of the blade tips is evaluated, although other points on the cutting tool may be used if desired. The program assumes that the gear is generated using the face milling process with zero cutter tilt. The program takes points $X_c = \langle x_c, y_c, z_c \rangle$ in the cutter coordinate system and transforms those points to the gear coordinate system $X_g = \langle x_g, y_g, z_g \rangle$. The z-axis of the cutter coordinate system is the axis of rotation of the cutting tool with positive z pointing into the cutter body. The cutter blade tips are located in the x-y plane of the cutter coordinate system. The origin of the gear coordinate system is the apex of the gear. The z-axis of the gear coordinate system is the axis of rotation of the gear. Rotation of the gear about its own axis does not affect the cutter path, and is not considered. The simplified coordinate transformation between the cutter coordinate system and the gear coordinate system is:

$$\begin{bmatrix} x_g \\ y_g \\ z_g \end{bmatrix} = \begin{bmatrix} \cos \Gamma & 0 & \sin \Gamma \\ 0 & 1 & 0 \\ -\sin \Gamma & 0 & \cos \Gamma \end{bmatrix} \cdot \left(\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} + \begin{bmatrix} s \cdot \cos(q + \Delta q) \\ s \cdot \cos(q + \Delta q) \\ 0 \end{bmatrix} \right) \quad (1)$$

$$- \begin{bmatrix} X_{SB} \cdot \sin \Gamma + X_{MCB} \\ E_m \\ X_{SB} \cdot \cos \Gamma \end{bmatrix}$$

Where Γ is the machine root angle, $(q + \Delta q)$ is the cradle roll position; X_{SB} is the Sliding Base, E_m is the machine offset; and X_{MCB} is the machine center to back. These values can be found in the grinding machine summary for the gear or for preliminary design they can be calculated from the gear tooth geometry (Ref. 2).

A two-dimensional visualization is created by plotting the distance of each point from the shaft axis $r_g = \sqrt{x_g^2 + y_g^2}$ vs. the position along the shaft axis z_g . The position of the cutting tool relative to the gear changes throughout the generating motion. This motion is a function of the parametric parameter $(q + \Delta q)$, the cradle roll position; therefore, multiple cradle roll positions should be plotted. For preliminary design, plotting the two extreme positions along with one central position appears to be

sufficient. Typically, multiple roll positions are presented on a single plot. Multiple points of interest on the cutting tool can also be plotted simultaneously if desired. Figure 3 shows an example output from the preliminary design tool showing the paths of multiple points on a grinding wheel at three different roll positions.

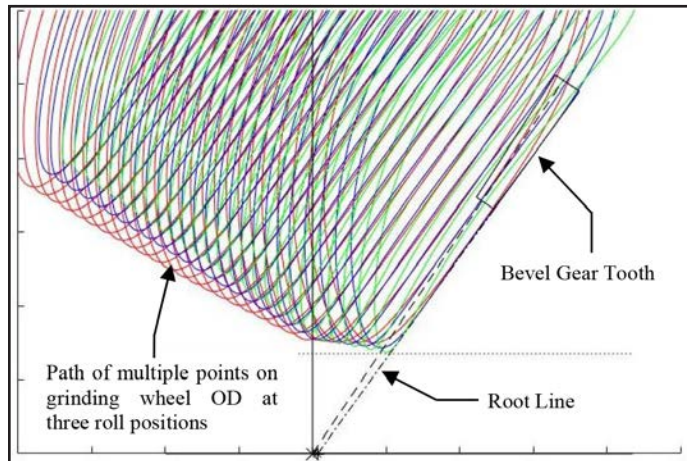


Figure 3 Sample output from the preliminary design tool.

Detailed Design

Once a preliminary design has been established, further refinement is needed to verify that the gear tooth cutting and grinding operations will not interfere with the shaft design. At this point further consideration must be given to the geometry of the cutter head and the machine to ensure there is no interference with the design. Coordinate points and unit normals calculated using the updated Preliminary Design tool were used to establish the location of the cutter head in a three-dimensional CAD model of the integral gear. A course representation of the cutter or grinding wheel was drawn in the integral gear CAD model at each of the three roll positions. Figure 4 shows the three cutter positions during the gear tooth machining process.

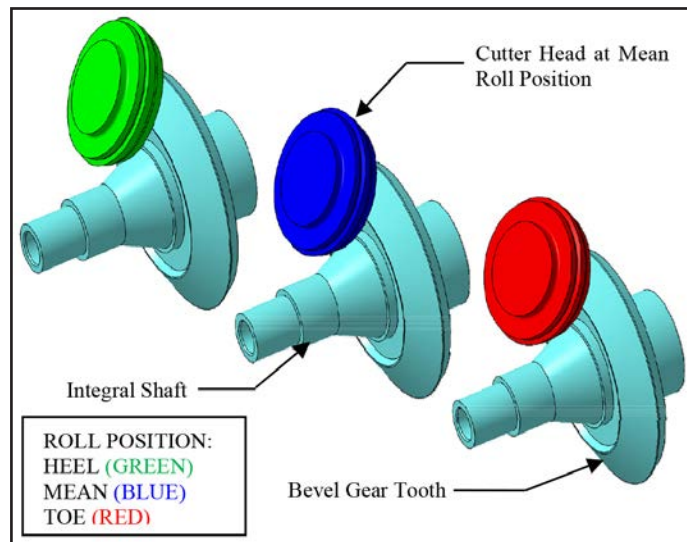


Figure 4 Cutter wheel located at the three roll positions in the integral shaft gear model.

The model was used to check clearance with the integral shaft design and to make changes to maintain the minimum clearance while meeting design goals. Changes can also be considered to the blade cutter or grinding wheel. Grinding wheels come in standard sizes, where only a small portion of the wheel is actively used for a job. Extra stock can be removed from the wheel by following the blade angle from the outer blade point or by reducing the diameter of the overall wheel. Reducing grinding wheel outer diameter also reduces wheel stiffness and can impact tooth accuracy, so the effort should focus on fitting the largest-diameter grinding wheel in the space available. The cutter head can be modified by reducing the height of the bolt heads or by using an integral cutter head and blades. Figure 5 details initial grinding wheel interferences and modifications made.

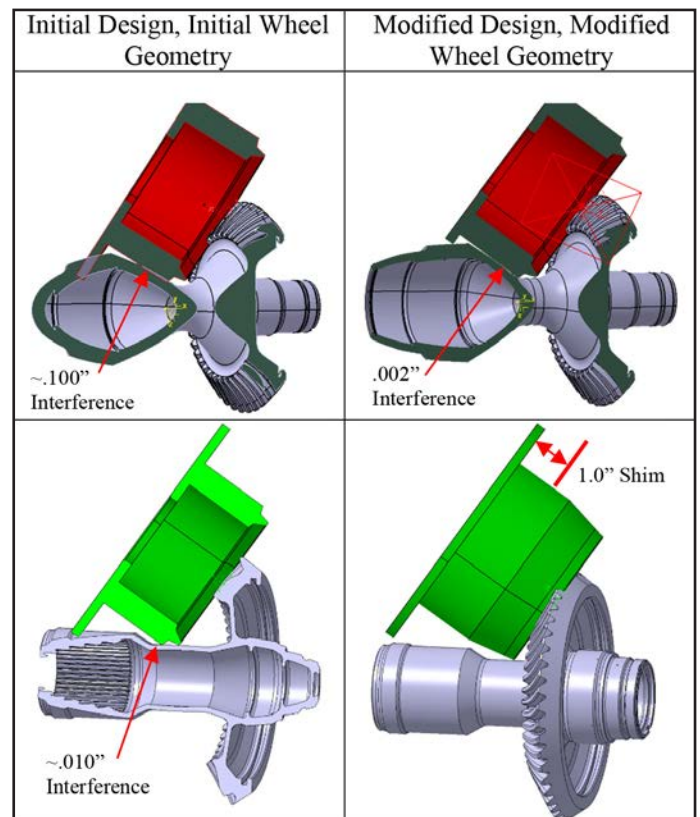


Figure 5 Examples of initial design integral shaft gears and grinding wheel interferences and modified designs and modified grinding wheels.

Both the grinding wheel and the cutter head can be shimmed away from the cradle base to eliminate collisions of the integral shaft bevel gear with the machine. In order to maintain accuracy of the bevel gear teeth, shimming should be minimized to keep the rigidity of the head. Care should be taken to fabricate a close tolerance shim that is perpendicular and concentric to the spindle axis to reduce runout and vibration in the spindle. Thought should be given to the number of dresses possible on the wheel before replacement, since with each dress the wheel height shortens and the gear shaft will move closer to the cradle base. Figure 6 shows an example of minimum distance from the cutter to the end of the shaft along the machine spindle axis.

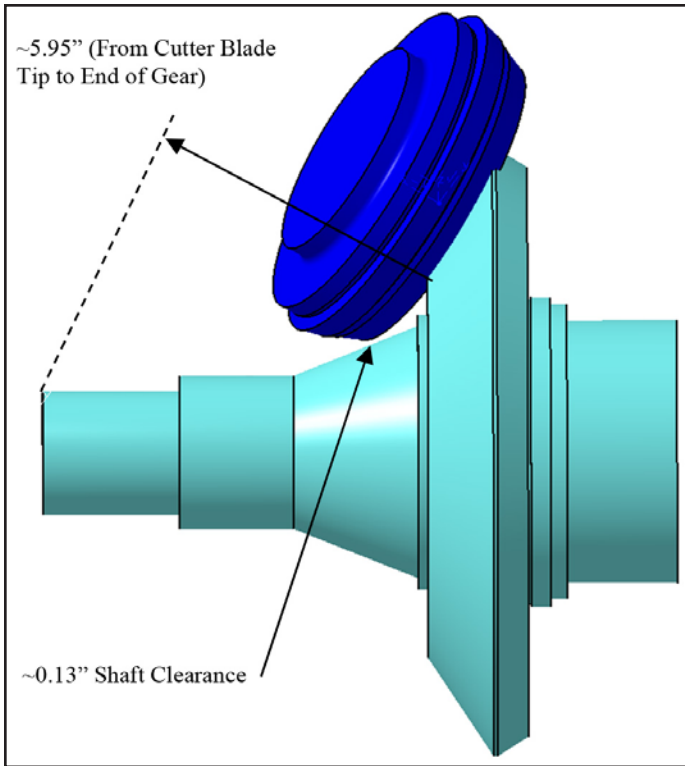


Figure 6 Minimum distance from cutter blade tip to end of gear along cutter spindle axis.

Manufacturing Trial

Once a workable solution was reached, trials were conducted in the gear manufacturing machine to verify that a solution had been found. Actual verification reduces schedule risk ahead of fabrication of the first part. As suggested by the Reference 1 paper, a two-dimensional cardboard silhouette, three-dimensional wood, aluminum, or plastic piece are acceptable choices at this step. A test piece was turned from aluminum that replicates the outside shape of the shaft. For the gear head, the test piece was turned to the root cone. Wheel modification suggestions from the computer work were incorporated into the gear tooth wheel. The gear tooth machine summary was loaded onto the machine for the trial so that machine motions will be the same as the actual part.

The trial was conducted by jogging the machine through motion while the spindle is not turning. The machine motion was stopped at toe, mean, and heel roll positions in order to measure clearances between shaft, wheel, and machine. The machine motion was again checked while the coolant bars and nozzles were in place. Figure 7 shows an example of the first and second iterations for the manufacturing trial in a gear tooth grinding machine shown at the toe roll position. In this case, the gear teeth were ground from solid and finish ground in the same machine.

In a different trial, the gear manufacturer planned to rough the gear teeth using a cutting process. Figure 8 shows the resulting integral shaft gear design during the gear tooth cutting process.

Following the Reference 1 paper, the grinding wheel dressing operation was also checked while the integral shaft part was installed. The check proved successful and did not impact any of the designs. One issue noted by the manufacturer was the motion from the home position to the first position before the

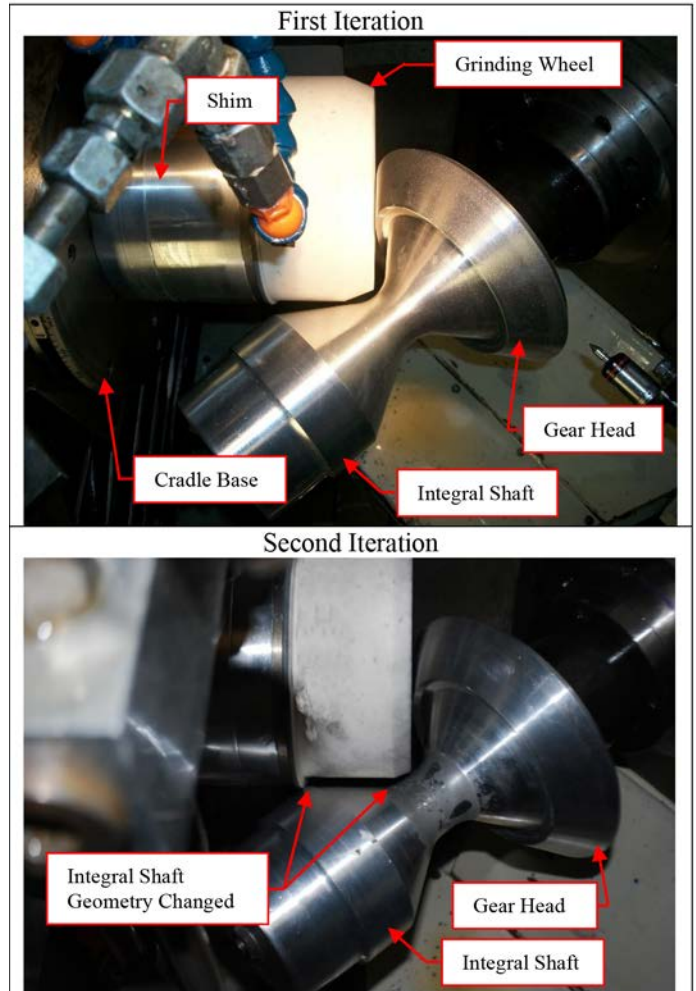


Figure 7 An example of the first and second iterations for the manufacturing trial in a gear tooth grinding machine shown at the toe roll position.

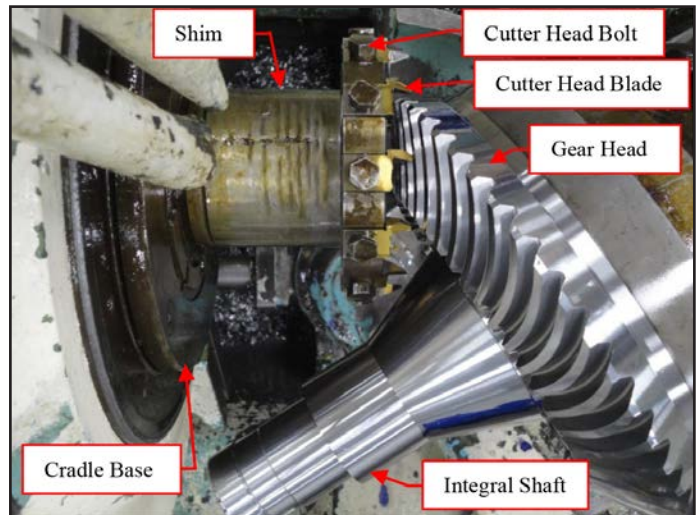


Figure 8 Example of an integral shaft bevel gear roughed by a cutting machine.

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wheel enters the tooth. The machines move to the first position by moving in all axes simultaneously. An issue arose in one instance, where the simultaneous motion caused the integral shaft to be in the way during the movement to the first position. The issue was rectified by switching the start and stop roll angles. If a case is presented where the machine tool must follow a path to reach the start position, the machine tool manufacturer would be integral to achieving a solution.

Conclusions

Techniques described were applied to the development of an integral shaft design for a growth project for the CH-47 Chinook and two designs for a new transmission design for the SB>1 DEFIANT aircraft for the Joint Multi-Role Technology Demonstrator Program.


A preliminary design simulation tool for cutter path tools was updated. A detailed design approach was developed to visualize the cutter head in three dimensional spaces in relation to the integral shaft gear design in CAD.

Concluding Recommendation

A successful integral shaft design requires input from design, stress, manufacturing, and the machine manufacturer. Further development in the virtual machine simulations could be used to provide stay out zones in the form of three dimensional surfaces when integral shaft designs are considered.

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References

1. Drago, Raymond J. "On the Design and Manufacture of Integral Spiral Bevel Gears for the CH-47D Helicopter," *AGMA Fall Technical Meeting*, Aerospace Gearing Committee Meeting, American Gear Manufacturers Association, Lake Tahoe, Nevada, March 1979.
2. Litvin, Faydor L. and Hong-Tao Lee. "Generation and Tooth Contact Analysis of Spiral Bevel Gears with Pre-Designed Parabolic Functions of Transmission Errors," *NASA Contractor Report 4259, AVSCOM Technical Report 89-C-014*, November 1989.
3. ANSI/AGMA ISO 23509-A08. Bevel and Hypoid Gear Geometry.

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