Good Basic Design or Sophisticated Flank Optimizations? Each at the Right Time

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More strength, less noise. Those are two major demands on gears, including bevel and hypoid gears. Traditionally, gear engineers have met the first demand by changing a gear set's basic parameters—tooth height, pressure angle, spiral angle, etc.—and met the second by making flank form modifications, also known as ease-off.

With today's computer technology, though, many engineers are modifying flank topography and discovering their gear sets are both stronger *and* quieter. Unfortunately, this coincidence is tricking some engineers into believing that ease-off itself adds strength to gear sets. In fact, the flank form modifications are only allowing the sets to make greater use of the strength that was possible in their basic designs.

Most strength optimizations require changing a gear set's basic parameters. Most minor reductions in gear noise are made by optimizing just flank topography. In some cases, though, there are gear sets that don't use all their possible strength because they need sophisticated ease-offs but lack them.

The challenge for gear engineers is to know when to change which, basic parameters or flank topography, to increase a gear set's strength. To know that, engineers need to understand both basic parameters and flank form modifications. The parameters are discussed in the side article, "Influences of Major Basic Parameters."

Changing Basic Parameters Not Always Possible

A gear set's basic parameters offer gear engineers many ways to optimize the set's performance, but changing them may not be an option in many cases. Gear engineers often must optimize for strength or noise in existing gear sets that have been in service for many years, but that need improvement because their gearbox requirements have changed. One example is a prime mover in which the gear set must transmit more power—but still fit in the same space inside the existing housing. Another example is a gear unit in which noise must be reduced.

Generally, a strength optimization requires a new or improved basic design. The exception is a gear set with an optimal basic design but with a conventional ease-off, one that allows for improvement. In that case, a gear engineer will significantly strengthen the set via sophisticated flank modifications. Such ease-off may be the engineer's only option if the space for the set can't be increased, as in the prime mover example.

In the other example, gear engineers are usually told not to change the noisy gear set's basic design. The reasons are time and money. If basic parameters are changed, the gear set will require a strength requalification. But requalifying an automotive axle drive unit, for example, may cost $40,000 and take six months.

Fortunately, sophisticated optimizations of flank form have a neutral or positive influence on a gear set's strength. It's widely accepted in the industry that a gear set with flank modifications doesn't need its strength requalified as long as the modifications didn't change the basic parameters. So, whenever possible, gear engineers would be well advised to follow this rule: "Keep the existing, proven basic design and adjust only the contact topography."

Flank Form Modifications

Flank form modifications are deviations from the correct, or conjugate, flank form. If a ring gear were used in a virtual process to generate a pinion, the result would be a pinion that has—at all times—line contact with one or more gear tooth flanks and rolls perfectly with no motion transmission error. This would be a conjugate tooth system.

But this system isn't possible in the real world. As gear engineers know, gear and pinion interaction is affected by manufacturing tolerances and load-dependent deflections of the gears, bearings and gear-

Influences of Major Basic Parameters

A gear set's basic parameters establish the potential of its properties, including strength and noise. There are many major basic parameters, and they have a variety of effects on the operating performance of a gear set. Gear engineers need to understand these effects, especially when optimizing gear sets.

A tall tooth is more elastic than a standard tooth. The tall one's thickness is less than the standard one's, but it isn't reduced by much. The tall tooth's height is limited to the minimum point width of the cutting blade. But the tall tooth has advantages over the standard one: higher effective contact ratio and lower impact intensity at the tooth entrance. In other words, there are strength and noise advantages without significant disadvantages.

A high spiral angle reduces normal tooth thickness and increases the theoretical contact ratio. The reduced thickness has a second order influence on root bending stress, reducing a gear's load carrying capacity. The higher contact ratio has a less than proportional influence on load sharing, but the teeth will mesh more smoothly and have reduced tooth impact excitations.

Reducing pressure angle increases the root and top widths of teeth. Given this effect, a gear engineer can increase tooth depth because blade point width and pointed tops won't reach their limits until much later.

A fine-pitch gear will have a higher contact ratio and proportionally shorter and thinner teeth than a coarse-pitch gear of the same circumference. These effects result from the fine-pitch gear having more teeth on its circumference. The fine-pitch gear will also make much less noise, but its load carrying capacity will be significantly lower.

A smaller face width means a low transverse contact ratio and a short contact pattern. It also means there will be a continuous risk of edge contact even when deflections under load are small. But a wider face width creates problems in manufacturing. Chips are too long, and heat treat distortion is significant. Moreover, a wider face width doesn't increase strength to the expected extent. Among bevels and hypoids, face width has an optimal value that is 33% of the ring gear's mean cone distance.

A hypoid offset lowers the center of gravity for rear-wheel-driven vehicles, but it creates relative sliding in the tooth lead direction, increased pinion diameter and a higher pinion spiral angle. The offset also leads to better hydrodynamic lubrication film, good dampening properties, higher overall contact ratio

Continued on page 23.

box. Line contact becomes edge contact along the teeth boundaries, and motion transmission takes on a saw-tooth profile. Moreover, bevel gears—which include hypoid gears—require relief in the profile and lead directions from their conjugate flank forms. This relief starts in a tooth's center and provides circular relief towards the tooth ends, top and root.

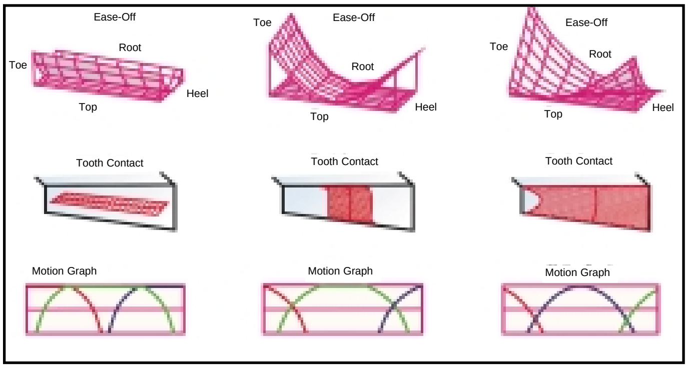

Figure 1— Profile crowning (left column), length crowning (center column), and flank twist (right column).

Today, the ease-off of a typical bevel gear set consists of a circular relief in the lead direction (length crowning), a circular relief in the profile direction (profile crowning) and a circular relief in the path-of-contact direction, diagonally across the flanks (flank twist). Figure 1 shows calculated contact analysis of these three basic corrections in three columns, with each ease-off on top, its tooth contact in the middle and its resulting motion graph on the bottom.

The latest computer developments also make it possible to apply higher order flank modifications along the path of contact. These modifications are created during the generating of pinions and gears via a machine's axes, through a combination of additional roll-position-dependent movements. All these modifications are plotted together over the tooth projection plane, just like the result of a coordinate measurement. This ease-off represents all deviations from the conjugate tooth system, regardless of whether the modifications were done in the pinion, the ring gear or both.

What Can Ease-Off Do?

Flank form modifications can be very powerful tools for noise and strength optimizations, especially since the modifications are available for the leading machine tool brands. Ease-off can increase strength if, for example, a gear set has a contact ratio that's lower—even much lower—than the ratio possible given the set's existing basic parameters. With the right modifications, the contact ratio can be increased, so the gear set makes greater, more efficient use of its existing basic properties. As gear engineers know, when contact ratio is increased, strength is increased.

Using higher order modifications, gear engineers may even be able to define different flank sections, allowing them to distinguish between the changing requirements of the contact entrance and exit areas as well as the mean contact section. Figure 2 shows a motion graph that can result from higher order flank form modifications.

Also, higher order modifications can improve load sharing between two or three consecutive pairs of teeth, decreasing surface compression stress and root bending stress, possibly by 25% or more.

A gear set's basic geometry defines the modified contact ratio as a result of profile and transverse contact ratio, but load sharing between consecutive pairs of teeth depends on the load and ease-off between meshing flanks. If the ease-off is parabola shaped (of second order) in the profile and lead directions, then the pair of teeth with contact areas close to the center transmits 60–90% of the load. Conversely, this ease-off decreases the load transmitted by the pair of teeth with contact towards the entrance area and the pair of teeth with contact towards the exit. Those pairs transmit only 10–40% of the load.

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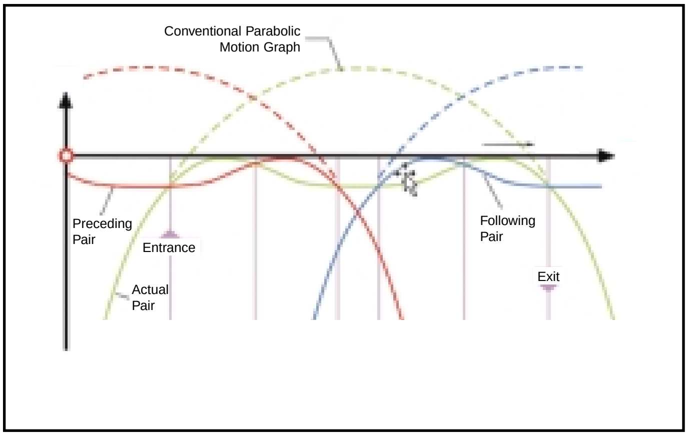

Figure 2— Sophisticated flank optimization with higher order motion graph.

Moreover, gear engineers can use a higher order ease-off to reduce the load transmitted by the pair of teeth with center contact. Such an ease-off can reduce it to 40%. This reduction in turn increases up to 60% the load transmitted by the pair with entrance contact and the pair with exit contact.

This effect has no drawback. The load distribution between consecutive teeth is more equal, so the load change in pairs of teeth during mesh is smoother and less abrupt, as shown in Figure 2. This is a win-win situation that is just now being used to its full extent in the gear industry.

In both cases—parabola shaped ease-off and higher order ease-off—the calculated contact ratio remains constant, but only the higher order ease-off uses the contact ratio more intelligently.

Gear engineers should be careful, though, if a noisy gear set has previously been optimized using higher order ease-off, such as Gleason UMC or Klingelnberg Modified Crowning, and the set's strength was based on the unconventional, optimized design. Focusing too much on the noise, an engineer might try to reduce the noise by superimposing additional higher order modifications on the existing ease-off. The new modifications might partly reverse the existing ease-off's positive effect, sacrificing the design's strength.

The engineer, however, can check on whether his noise optimizations sacrificed strength by using finite-element calculation systems dedicated to high-accuracy calculating of gears. These systems can be used to verify a gear set's before and after situations. However, if the calculation shows an increase in critical stress, the engineer would have to change the basic design to keep the stress below the required limits and to enhance the transmission quality.

Conclusions

Gear engineers should be aware that basic gear design parameters create the foundation for a gear set's properties and that flank form modifications can help the set fully realize its properties. A bad ease-off, even a conventional one, will keep a gear set from achieving the potential offered by its properties. A good ease-off will allow it to achieve its potential by taking optimal advantage of those properties. By optimally combining basic design and flank modifications, gear engineers can create gear sets that are able to transmit twice as much torque as other sets of the same size and still be quieter than those other sets.

Generally, a strength optimization requires a new basic design. The exception is a basic design that is found to be optimal but the ease-off is conventional and leaves room for improvement; here a sophisticated flank modification will make a big difference and might be the only possibility if the space of the gear set can't be increased.

A noise optimization generally requires a flank modification only. The exception here is if the gear set already employs higher order flank modifications. In that case, the noise reduction may not be easily possible. If an improvement still seems reasonable, a finite element calculation of the before and after situations is necessary. If the calculation shows critical stress is increased, the gear engineer will need to change the basic design to keep the stress below its required limits and to reduce noise through better transmission quality.

Gear engineers should see the possibility of developing a new basic design as a great chance, not as a burden. They should always start with the previous design because they may be able to make many small improvements to better adjust the gear set to its changed requirements. Also, they should never make the mistake of thinking that the effort of thoroughly developing the basic parameters can be reduced to making only higher order flank form modifications. They must always remember the rule: "The basic design parameters set the direction for the gear set's properties, sophisticated flank form modifications will only give us better access for realizing the properties' potential."

Continued from page 21.

and increased pinion strength.

Whenever possible, gear engineers should design bevel gear sets to include hypoid offsets—that is, they should design hypoid gear sets. A hypoid gear pair is preferable to a spiral bevel gear pair because the hypoid offset provides strength and noise advantages that are significant and should not be underestimated. However, the hypoid set requires high pressure hypoid oil, so it will have scoring resistance. Also, if the offset is too high, the sliding velocity causes increased operating temperature, additional energy loss and the risk of scoring. The optimal hypoid offset lies between 10% and 20% of the ring gear diameter. The coolest running bevel gears are hypoids with an optimal offset: Their efficiency and strength are unbeatable compared with spiral bevel gear sets.

A small cutter radius increases a gear set's contact ratio. It does so because, compared with a conventional or large cutter radius, a small one increases spiral angle on the heel and decreases the "natural" loaded contact movement towards the heel. So gear engineers should choose a cutter diameter that allows the mean contact point to move from light load to maximal load using about 30–50% of the face width, while the contact area increases to cover the entire flank area without hard edge contact. However, an engineer's choice of cutter diameter depends on displacement between pinion and gear under load in a gearbox housing.

A face-hobbed tooth surface, when lapped, will present an optimal condition for smooth operation. This surface depends on face hobbing because the machining flats and contacting lines between pinion and gear cross each other under an angle that provides pockets for the lapping compound. In face milling, the flats and lines are parallel, so they don't create pockets. When a face-hobbed gear set is rolled in a lapping machine, the compound will fill the pockets so only the peaks of the machining flats have contact at the start of lapping. This contact leads to initial material removal that is rapid but uses low torque only.

As lapping progresses, this rapid removal reaches its natural end when 90% of the cutting structure is removed. For face hobbing, like for face milling, a gear engineer should pick a cutter radius that optimally controls loaded contact movement.

Gear engineers should also keep in mind: If the cutter has a high number of starts, the tooth lead function will approximate the shape of an involute. This approximation results in a gear set with additional insensitivity to deflection. In particular, it protects the teeth from edge contact in high load situations.