Designing Hardened & Ground Spur Gears to Operate With Minimum Noise

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When designing hardened and ground spur gears to operate with minimum noise, what are the parameters to be considered? Should tip and/or root relief be applied to both wheel and pinion or only to one member? When pinions are enlarged and the wheel reduced, should tip relief be applied? What are the effects on strength, wear and noise? For given ratios with enlarged pinions and reduced wheels, how can the gear set sizes be checked or adjusted to ensure that the best combination has been achieved?

This is a complex question, requiring consideration of both rating and noise. Three of our technical editors have reflected on the subject.

Robert E. Smith replies: The primary consideration for the minimization of noise is to reduce tooth-to-tooth transmission error under the loaded operating conditions. This means making the teeth as conjugate as possible under load; a true involute running with a true involute. For lightly loaded gears, this means making the involutes as perfect as possible. For gears operating under significant loads, the teeth can have profile modifications in the form of tip or root relief to allow for tooth deflections such that they are true involutes when loaded.

Even with profile modifications, there are a couple of other subtle problems that can cause noise that is objectionable to the human ear. Many times unground gears can be less accurate, yet sound more pleasing to the ear than precisely ground gears. This is because random spacing errors and runout or accumulated pitch errors cause a masking noise that tends to cover up the pure tones and harmonics that are generated by the mesh frequencies. The accumulated pitch errors can cause sidebands of mesh frequency that appear like a "white noise" floor level in the spectrum. When grinding gears, it is not unusual for this background noise to be much lower than the gear mesh frequencies. This makes the pure tone effects more objectionable to the human ear, even though the overall dbA level may be the same.

The second subtlety comes from a phenomenon called "ghost harmonics." This is usually a high pitched noise that is caused by waviness in the profile or lead of the teeth. These waves are commonly called undulations. The critical ones lie parallel to

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the instantaneous line of contact. They are caused by the final drive gears of the work spindle on the gear generating machine. There will be an integer number of waves in one revolution around the gear being manufactured, and the number will be the same as in the final work spindle drive gear. The result can be a very small waviness in the involute profile and/or lead charts and is frequently ignored in the assessment of these charts. The waviness can often be smaller in amplitude than .0001", yet cause significant noise. However, these peaks can be detected by single flank transmission error testing, as well as by noise analysis through the use of an FFT analyzer. If you know the number of teeth in the final work spindle drive gear, you can predict where the peaks will be found in the spectrum.

A good practical guide to the application of profile modification may be found in the *Gear Handbook*, McGraw-Hill, 1962, Chapter 5, pp. 22 and 23, by P. Dean. He states: "In general, gear teeth which carry a load in excess of 2,000 lbs. per inch of face width for more than a million cycles should be modified. Those under 1,000 lbs. per inch of face do not generally require modification." Formulas for the amount of tip relief on the driving and driven gears are given in this reference. Another reference is the *Handbook of Practical Gear Design*, McGraw-Hill, 1984, by Dudley. This contains several sections on profile modification and generally indicates putting tip relief on both members.

From a noise reduction standpoint, the best advice is not to use more profile modification than is absolutely necessary. It can cause a rapid loss of profile contact ratio and conjugacy. Start out with little or none in order to meet the noise requirements and then life test to see if the parts will survive. Many people start with too much modification, in anticipation of tooth failure, and then wonder why the gears are noisy.

Bob Errichello replies: One of the most important decisions a gear designer makes is selecting the number of teeth in the pinion. There is a preferred number that provides a good balance between pitting resistance, bending strength and scuffing resistance. See AGMA 901-A92 for an algorithm for calculating the preferred number of teeth.

Profile shift (enlarging/reducing) is used to

- Prevent undercut
- Balance specific sliding
- Balance flash temperature
- Balance bending fatigue life
- Avoid narrow top lands.

The profile shift should be large enough to avoid undercut and small enough to avoid narrow top lands. In general, the profile shifts for balanced specific sliding, balanced flash temperature and balanced bending fatigue are different, but nearly the same if the pinion has the preferred number of teeth (see AGMA 901-A92).

Profile modification is used to minimize the detrimental effects of tooth deflections, assembly tolerances and tooth variations. Proper profile modification increases load capacity and reduces noise.

Fig. 1 shows the interference that

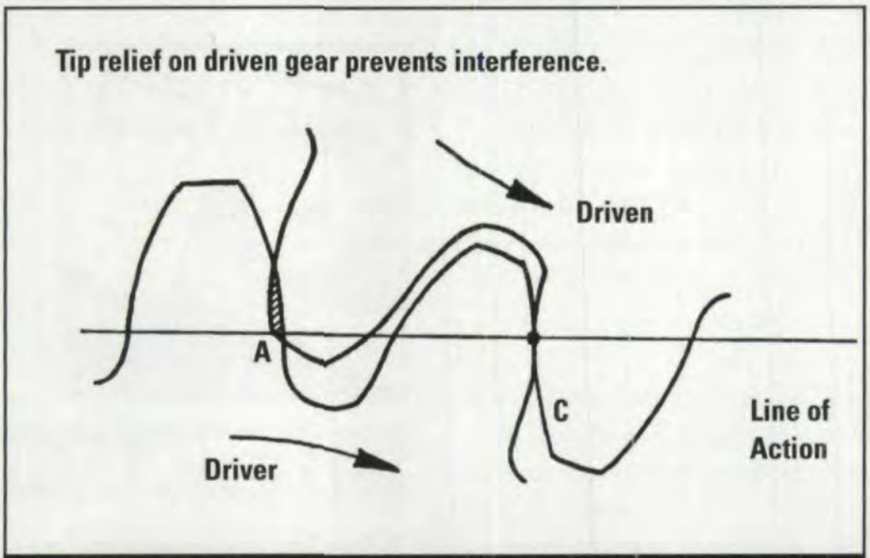

Fig. 1 – Interference occurring at last point of contact (Point A).

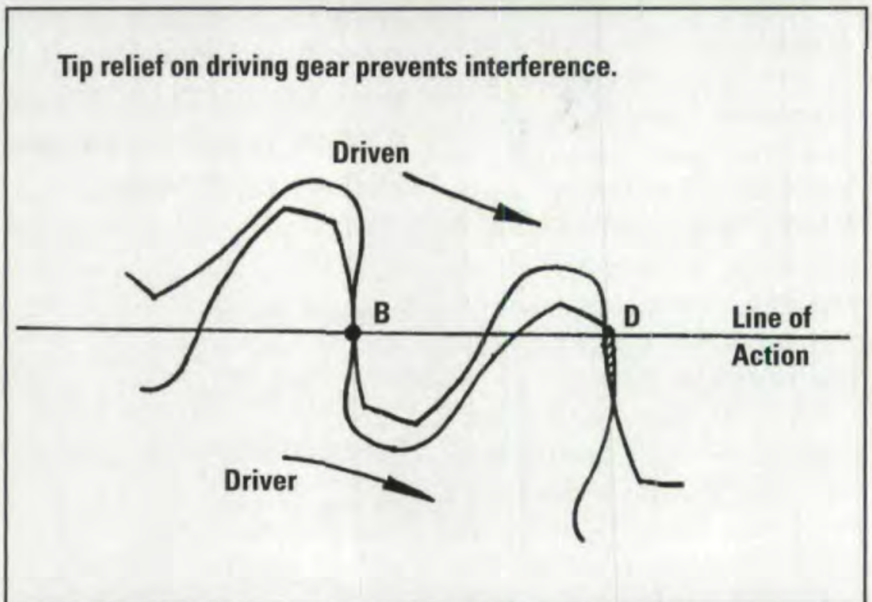

Fig. 2 – Interference occurring at last point of contact (Point D).

occurs at the first point of contact (Point A) with unmodified involutes. The interference is due to deflections of the pair of teeth in contact at Point C, which lengthen the base pitch of the driven gear and shorten the base pitch of the driver. The interference can be eliminated by profile modification that removes material from the tip of the driven gear (shaded zone in Fig. 1).

Fig. 2 shows interference at the last point of contact (Point D) with unmodified involutes. The interference is due to defections of the pair of teeth at Point B, which lengthen the base pitch of the driving gear and shorten the base pitch of the driven gear. The interference can be eliminated by profile modification that

removes material from the tip of the driving gear (shaded zone in Fig. 2).

Experience shows that the profile modification should be larger at the first point of contact than at the last point of contact. Generally the first point of contact is more critical because the oil film is not well developed and the frictional forces are higher as the gear teeth approach the pitch point rather than recede from it.

With speed reducers, the first point of contact is at the start of active profile (SAP) of the pinion teeth where they are especially susceptible to pitting.

With speed increasers, the first point of contact is at the tip of the pinion teeth and the SAP of the gear teeth where both members are especially susceptible to scuffing.

With regard to the kinematics of the gears, it does not matter whether the material is removed in the form of tip relief or root relief. However, the involute profile is more difficult to control near the base circle because the curvature is rapidly changing. Therefore, tip relief is generally preferred over root relief for ease of manufacturing.

Don McVittie replies: The parameters to be considered in determining the amount of profile shift and the distribution of profile shift between gear and pinion are best covered in AGMA 901-A92, *Rational Procedure for the Design of Minimum Volume Gears*, Annex A. The Maag *Gear Book* also has good basic information on why and how. Both are available from AGMA.

Parameters which reduce noise are usually:

- High accuracy, particularly small adjacent pitch variation, good helix (lead) matching and convex rather than concave involute profile deviation.
- High transverse contact ratio. The following increase it:
  - Low operating pressure angles
  - High numbers of teeth
  - Long (extra depth) teeth
  - High axial contact ratio — 2.0 or more. It is increased by:
  - Higher helix angles
  - Finer pitches — smaller modules
  - Wider face width may be bene ficial, but can cause problems with lubrication and load distribution.
  - Some engineers strive for integer values of axial contact ratio, believing that this reduces the variation in stiffness caused by the variable length of the helical lines of contact. This is probably most important with axial contact ratios less than 2.0.

The optimum design varies, depending on the application. For example, the best practice for industrial conveyor drives is much different from that for marine reduction gears or automotive gears. Usually some compromise is required between optimum design for bending strength and optimum design for minimum noise. An optimum design for pitting resistance can be a good starting point. The vibration response of the housing can also be important. A light weight housing with many low natural resonance frequencies will respond to excitations from the gear teeth which wouldn't be important in a heavier housing with higher natural resonant frequencies.

Tip relief can be applied as tip and root relief on the pinion or as tip relief on both gear and pinion. With the pinion driving, the required gear tip relief or pinion root relief is usually about 1/3 more than the required pinion tip relief. It is hard to manufacture accurate pinion root relief if the pinion's start of active profile is near the base circle. Sometimes it's impractical to achieve the required root relief in a few degrees of roll near the pinion base circle, so both parts are tip relieved.

In the U.S., stock hobs used to be furnish with a "ramp," an area of higher pressure angle near the root of the hob tooth, which cut tip relief in both gear and pinion. The amount of tip relief on the part varied with the number of teeth and the profile shift, so the effect was hard to control. Most manufacturers now achieve tip and root relief by grinding or by shaving with specially designed cutters.

For a discussion of how much tip relief to allow and where to start modification on the profile, see Dudley's *Handbook of Practical Gear Design*, pages 8.12 through 8.21.

Properly designed and manufactured tip and root relief on spur gears or tip, root and end relief on helical gears reduce dynamic load by assuring smooth meshing as the teeth engage and disengage at the ends of the lines of contact. Reduction of the dynamic load is beneficial for strength, pitting resistance and noise. It also encourages the formation of an oil film between the teeth which reduces the tendency toward micropitting and abrasive wear. The benefits apply to all heavily loaded gears with or without profile shift. ■