A better way to design gears for medical devices

The Direct Gear Design method does not use basic rack parameters. It starts, instead, with performance requirements and operating conditions to define the gear shape.

The asymmetric gears are in an experimental medical pump on a therapeutic cooling system and were designed by the Direct Gear Design method. The gears are made of PEEK for a variable speed and load. Some of the prototype gears were machined and some were molded. The 6-tooth asymmetric spur gears have pressure angles of 45.7 and 10.3° for better performance.

Alexander L. Kapelevich
AKGears LLC
Shoreview, Minn.
akgears.com
Thomas M. McNamara
Thermotech Co
Hopkins, Minn.
thermotech.com

The performance priorities for gears in medical devices differ considerably from many traditional applications. Medical applications are more likely to include space limitations (miniature gear drives), high speeds, low or no noise operations, restricted use of lubricants, and disposability. In addition, gears for medical tasks are made from non-traditional materials such as soft polymers and harden stainless alloys.

Traditional or standard gear design is based on a basic or generating gear rack. Its parameters (profile angle, addendum, whole depth, and fillet radius) have been standardized by organizations including ASME, AGMA, ISO, and DIN. Typically, the 20° pressure angle and other basic gear rack dimensions are starting points for a design. Benefits of designing this way include gear interchangeability and a low tooling inventory.

Traditional design allows modifications to addendums to alter gear performance for say, higher efficiency or load capacity. But there are shortcomings.

For further reading

Townsend D.P. ***Dudley's Gear Handbook***, McGraw-Hill, 1991.

V. I. Goldfarb, A. A. Tkachev, ***New Approach to Computerized Design of Spur and Helical Gears, Gear Technology***, January/February 2005, 27 to 32.

E. B. Vulgakov, ***Gears with Improved Characteristics***, Mashinostroenie, Moscow, 1974 (in Russian).

A. L. Kapelevich, R. E. Kleiss, ***Direct Gear Design for Spur and Helical Involute Gears, Gear Technology***, September/October 2002, 29 to 35.

A. L. Kapelevich, Y. V. Shekhtman, ***Direct Gear Design: Bending Stress Minimization, Gear Technology***, September/October 2003, 44 to 47.

Limitations to traditional design

Selecting a standard basic rack imposes limitations on gear performance because all possible gear solutions for an application are inside a so-called block contours. But there is a clear trend to gear customization, so to improve gear performance beyond the block-contour limit, designers should consider nonstandard basic racks or individual basic racks for the mating gears.

Most medical gears, on the other hand, are designed for a particular application. The interchangeability of traditionally designed gears provides no benefit. And low tooling inventory is not that important. Besides, hobbing a gear, which uses the rack as a cutting tool, is not as dominant in gear production as it once was. Gears are also made by profile cutting, grinding, broaching, and others methods. Many medical gears are formed by precision forging, casting, extrusion, powder metal processing, plastic and metal injection molding and more. None of these methods use generating racks.

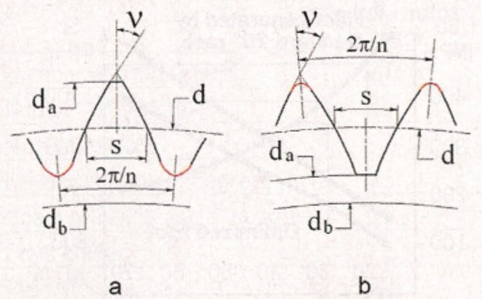
The proposed Direct Gear Design method uses no rack parameters. Instead, it uses the required performance parameters and operating conditions to define the gear shape. The idea behind Direct Gear Design (DGD), used successfully by engineers centuries ago, is to first define the gear geometry. In other words, gear parameters are primary, and the manufacturing operations and tool characteristics are secondary.

Gear tooth and mesh synthesis

There is no need for a basic (or generating) gear rack to describe a gear-tooth profile. Two involutes of the base circle, the arc distance between them, and tooth tip circle describe the gear tooth. Equally spaced teeth form the gear. The fillet between teeth is not in contact with the mating teeth. However, the fillet gets lots of attention because material there carries the maximum bending stress.

Defining the tooth-fillet profile completes the nominal gear geometry description. In traditional

Gear nomenclature

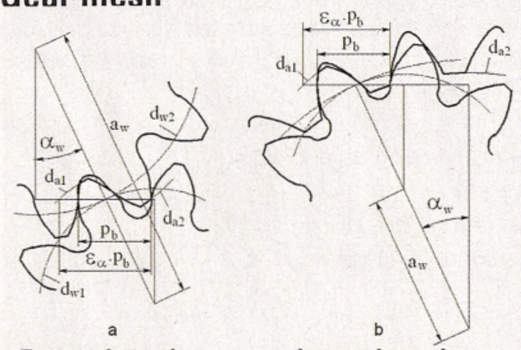


a
External tooth

b
Internal tooth

Tooth profile (the fillets are red)
d_a = tooth tip circle diameter
d_b = base circle diameter
d = reference circle diameter
S = circular tooth thickness at the reference diameter
v = involute intersection profile angle

Gear mesh



a
External gearing

b
Internal gearing

a_w = center distance
p_b = base circle pitch
α_w = operating pressure angle
ε_α = contact ratio
$d_{w1,2}$ = operating pitch circle diameters. Subscripts "1" and "2" are for the mating pinion and gear

gear designs, the fillet profile is a trajectory of cutting tool edges. The most common way to reduce bending stress concentrations in the fillet uses a full radius generating rack. In some cases, the generating rack tip is formed by parabola, ellipsis, or other mathematical curves. All these approaches have limited effect on reducing bending stresses, which depend on the generating rack profile angle and number of gear teeth.

In DGD, optimization of the fillet profile allows minimizing bending stress. The initial fillet profile is a trajectory of the mating gear's tooth tip in a tight (zero backlash) mesh. FEA and a random-search method can optimize the fillet. It should have minimal radial clearance with the mating gear tooth, excluding interference at the worst tolerance combination and operating conditions. With a maximized curvature radius, the fillet distributes the bending stress along a large portion of it, thereby reducing the stress concentration. The optimized fillet profile depends on the mating gear geometry and if the same gear is in mesh with an external or internal gear, or a gear rack. In practice, however, it does not depend on the load or its application point. If the gear is in mesh with several different gears, as in the planetary stages, the profile is optimized to exclude interference with any gear.

The graphs in *Contact stress reduction* and *Increased mesh efficiency* are for gears with standard and optimized fillets, different number of teeth, and for pairs with a constant center distance, a_w = 60 mm. The face width of both gears, b, is 10 mm. Driving torque, T, is 50 Nm. The graphs show that when gears with a standard and optimized fillet have the same acceptable bending stress level, gears with optimized fillet have finer pitch (smaller module) and greater number of teeth. This results in a contact stress reduc-

A little gear math

The equations here describe a few of a gear tooth's characteristics. Two or more gears with an equal base circle pitch can be put in mesh. The operating pressure angle, αw , and contact ratio, εα, are defined for external gearing by:

$\alpha_w = \text{arcinv}\ [(\text{inv}\ \nu_1 + u\ \text{inv}\ \nu_2 - \pi/n_1) / (1 + u)]$

$\varepsilon_\alpha = n_1[\tan \alpha_{a1} + u \tan \alpha_{a2} - (1 + u) \tan \alpha_w] / 2\pi,$

And for internal gearing by:

$\alpha_w = \text{arcinv}\ [(u\ \text{inv}\ \nu_2 - \text{inv}\ \nu_1) /(u - 1)]$

$\varepsilon_\alpha = n_1\ [\tan \alpha_{a1} - u \tan \alpha_{a2} + (u - 1)\tan \alpha_w] / 2\pi.$

In these equations:

$u = n_2/n_1$

where u = the gear ratio, n_1 is the number of pinion teeth, and n_2 is the number of gear teeth.

$\alpha_a = \arccos(d_b/d_a)$

where α_a = the involute profile angle at the tooth tip diameter, d_b = diameter of the internal gear, and d_a = external gear.

For metric system gears the operating module is

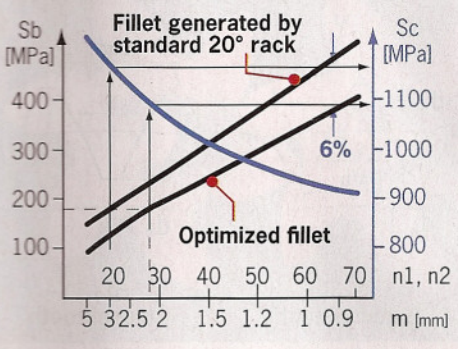
$m_w = 2a_w/(n_2 \pm n_1).$

For English-unit gears, the operating diametral pitch is

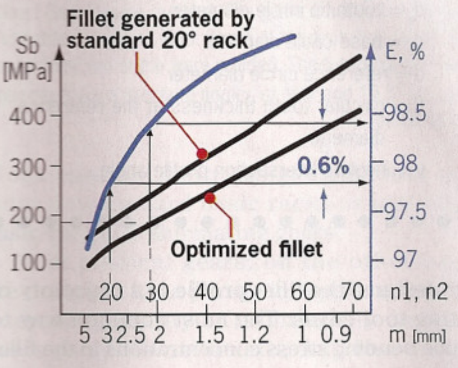
$p_w = (n_2 \pm n_1) /(2a_w)$

Use the + for external gearing and the - for the internal gearing.

Contact stress reduction



Increased mesh efficiency



tion because of the increased contact ratio and reduced tooth sliding increases mesh efficiency.

Bending-stress balance

Mating gears should have equal strength. If the initial bending stresses for pinion and gear differ significantly, the bending stresses should be balanced. DGD finds the optimum tooth thickness ratio, S_{w1}/S_{w2}, using FEA and an iterative method, providing a bending-stress difference of less than 1%. If the gears are made of different materials, bending safety factors should be balanced.

DGD works for all types of involute gears: spur, helical, bevel, worm, and face gears. The helical, bevel, and worm gear tooth profile is typically optimized in the normal section. The face gear fillet differs in every section along the tooth line. Therefore, DGD finds the optimized profile for each of several sections and blends them into the fillet surface.

Gears with asymmetric teeth

Two profiles (flanks) of a gear tooth are functionally different for many gear drives. In many gear applications the workload on one profile is significantly higher and applied for longer periods than for the opposite one. The design of an asymmetric tooth shape uses this functional difference. Gears with asymmetric teeth are suitable for DGD because there are no standards for asymmetric basic or generating racks. The design intent of asymmetric gear teeth is to improve performance of the primary drive profiles by allowing some performance reduction on the opposite side or 'coast' profiles, which are unloaded or lightly loaded during relatively short work periods. An advantage of asymmetric gears is a contact-stress reduction, resulting in higher torque density or load capacity per gear size. Another important advantage is the possibility for designing opposite flanks and fillets independent of drive flanks. Doing so manages tooth stiffness and load sharing while keep-

How fillet optimization lowers bending stress

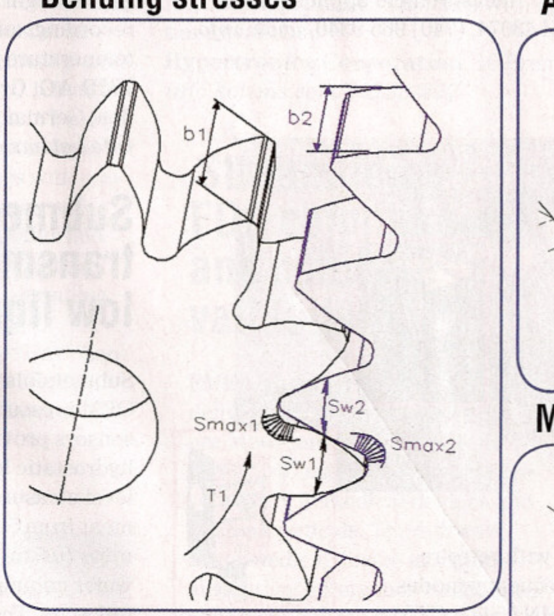
Number of teeth	Bending stress reduction in comparison with a standard 20° rack, %		Bending stress reduction in comparison with a standard 25° rack, %	
	Full radius 20 ° rack	Optimized fillet	Full radius 25° rack	Optimized fillet
12	-	-	8	21
15	6	25	7	20
20	10	23	6	18
30	10	21	6	17
50	10	21	5	15
80	10	21	5	14
120	10	21	4	13

Comparing traditional to Direct Gear Design gears

Characteristic	Traditional design with full radius 25° rack	DGD symmetric gear	DGD asymmetric gears	DGD Symmetric HCR gears	DGD asymmetric HCR gears
Number of pinion teeth	27	27	27	27	27
Number of gear teeth	49	49	49	49	49
Module, mm	3.0	3.0	3.0	3.0	3.0
Drive press angle, degrees	25	25	32	20	24
Coast pressure angle, degrees	25	25	18	20	16
Drive contact ratio	1.5	1.5	1.5	2.06	2.06
Pinion torque, Nm	300	300	300	300	300
Pinion bending stress, MPa	196	167	171	128	130
Gear bending stress, MPa	198	167	171	125	128
Contact stress, MPa	976	976	887	822	777

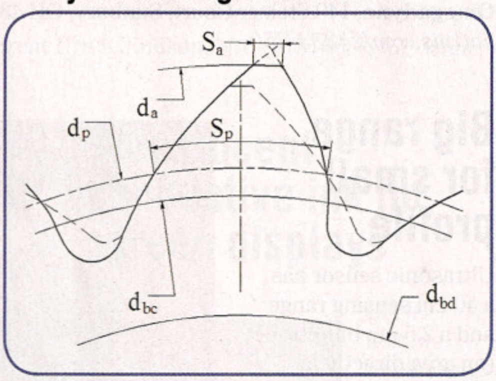
HCR refers to a high contact ratio.

Bending stresses

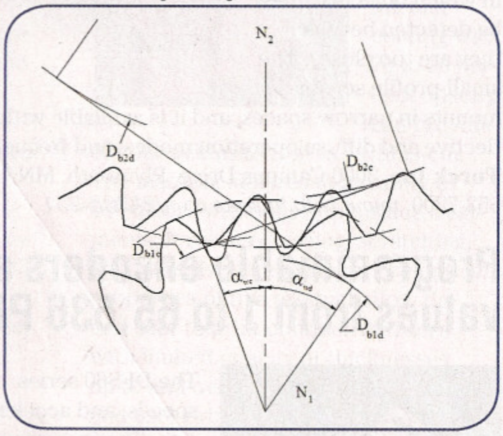


Bending stresses should be balanced in pinion and gear.

Asymmetric gear mesh



Medical pump



The asymmetric gear mesh represents different drive and coast flank meshes with different pressure angles and contact ratios.

ing a required pressure angle and contact ratio on the drive profiles. This reduces gear noise and vibration.

The DGD approach works the same for symmetric and asymmetric gears. The only difference is that an asymmetric tooth is defined by two involutes of two different base circles. A common base tooth thickness does not exist in the asymmetric tooth. The circular distance (tooth thickness), S_p, between involute profiles is defined at a reference circle diameter, d_p, that should be larger than the largest base diameter.

Asymmetric gears make it possible to simultaneously increase the transverse contact ratio and operating pressure angle beyond conventional gear limits.

With regard to manufacturing, optimized gear profiles will require custom tooling. For profile machining, a tool's profile is the same as a space profile between neighboring teeth. For a generating machining process, such as gear hobbing, a tool profile is defined by reverse generation, i.e., when the designed gear forms the tooling rack profile. The pressure angle, in this case, is selected to improve machining conditions. For molded gears, powder metal processing, and casting, the tool cavity profile is the same as the whole gear profile but adjusted for warp and shrinkage.

In summary

Direct Gear Design is driven by the application when technical and market performance of a product is critical. It provides complete gear tooth profile optimization resulting in significant reduction in contact and bending stress. This stress reduction can be converted to higher load capacity, lifetime, efficiency, reliability, and reduced cost, size and weight, noise and vibration. These performance advantages can benefit any medical product containing gear drives.