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Thinking outside the gearbox

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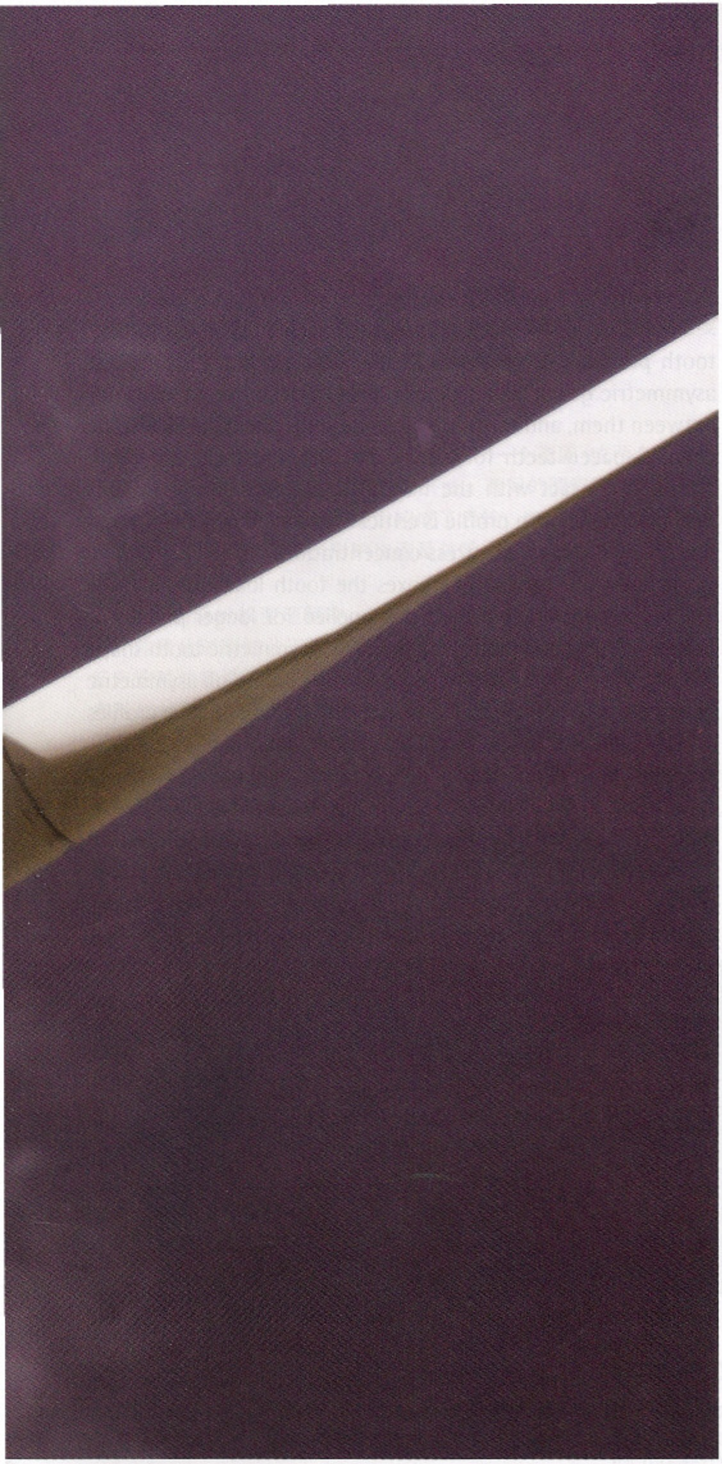
变速箱内的齿轮齿几何量近年已经发生了少许变化
Gear tooth geometry in gearboxes has seen little change in recent years

设计出变速箱——风力涡轮机加速器比较设计

Thinking out of the gearbox – alternative design for wind turbine speed increasers



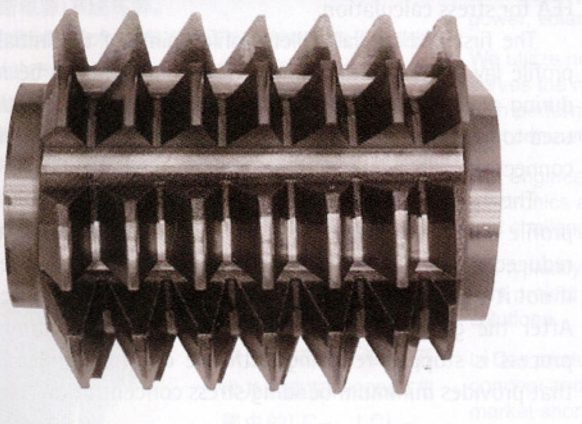
Innovation in wind turbines has increased the efficiency of wind power over recent years, but one component has been left behind in the drive for improvements, the humble gear tooth geometry. That is until now with a radical new design promising to deliver higher load capacity and reduced cost

The WindPower 2009 Conference and Exhibition (Chicago May 4 – 7, 2009) was an impressive demonstration of the latest and greatest achievements in all areas of science and technology related to the wind power generation. The wind turbine gearbox suppliers also presented the top notch of the gear alloys, gear forging and cutting processes, the mirror like looking tooth surfaces achieved by the isotropic super finish technology, the best bearings and lubrication systems.

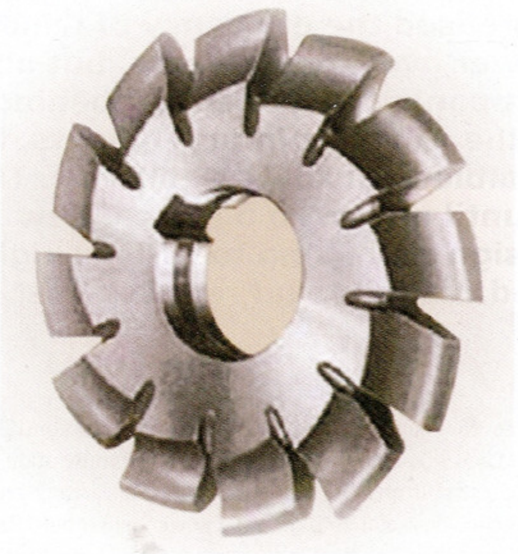
In contrast with all of these innovations the gear tooth geometry of almost all gearboxes looks obsolete. In most cases it presents the over one hundred years old tooth proportions produced by the standard 20o pressure angle generating racks with some addendum modification. This tooth geometry is universal and good for general gear applications, because of gear interchangeability and availability of the standard tooling. However, it does not fit to the specific operating conditions and requirements of the wind turbine gearboxes, which include long (over 20 years) lifetime, relatively low speeds, high static loads, size and weight constraints, high efficiency, noise and vibration limitations, low cost of fabrication and maintenance. The gear tooth geometry must be customised to satisfy all of these conditions.

Unlike the traditional standard gear design, the proposed alternative Direct Gear Design method does not use the basic rack parameters. It uses desired performance parameters and operating conditions to define the optimised gear tooth shape.

This design approach is developed for involute gears and based on the Theory of Generalised Parameters created by Prof. E B Vulgakov and can be defined as an application driven gear drive development process with primary emphasis on performance maximisation and cost efficiency without concern for any predefined tooling parameters.



为产生加工过程，如滚齿，齿形被反向产生定义
For generating machining process like gear hobbing the tool profile is defined by reverse generation



最优化齿形要求客户工装
The optimised gear profiles require the custom tooling

近年来，风力涡轮机的创新已经提高了风力的效率，但一个因素在改进过程中拖了后腿，即小齿轮齿几何量。直到现在才有一个激进的新设计有望提高负载容量并降低成本

2009年风能大会（2009年5月4-7日，芝加哥）是风力发电科学和技术所有领域的最新和最大成就的一次令人印象深刻的展示。风力涡轮机变速箱供应商也提供了先进的齿轮合金、齿轮锻造和切削工艺、各项同性超精细技术加工的镜面齿面、最佳的轴承和润滑系统。

相比这些创新，几乎所有变速箱的齿轮齿几何量看起来都很过时。大多数是超过100年的老式齿比例，这些是由带有齿顶高修正的标准20° 压力角齿条形刨齿刀生产的。由于标准工装的齿轮可互换性和可用性，齿几何量通用并有益于一般齿轮应用。但它不适于风力涡轮机变速箱的特定运行条件和要求，这种变速箱具有长寿命(20年以上)、相对低速、高静态负载、尺寸和重量限制、高效率、噪音和振动限制、制造成本和维护成本低的特点。

和传统的标准齿轮设计不同，提议的备选直接齿轮设计法不使用基本的齿条参数。它使用期望的性能参数和运行条件来定义最佳齿轮齿形。

Gear tooth and mesh synthesis

There is no need for a basic gear rack to define the gear tooth profile. Two involutes of one base circle (or, in case of asymmetric gears, two different base circles), the arc distance between them, and tooth tip circle describe the gear tooth. The equally spaced teeth form the gear. The fillet between teeth is not in contact with the mating gear teeth. However, this portion of the tooth profile is critical because this is the area of the maximum bending stress concentration.

In the wind turbine gearboxes the tooth load on one drive flank is significantly higher and is applied for longer periods of time than for the opposite coast one. An asymmetric tooth shape reflects this functional difference. Design intent of asymmetric gear teeth is to improve performance of the primary drive profiles at the expense of the performance for the opposite coast profiles. The coast profiles are unloaded or lightly loaded during relatively short work period. Asymmetric tooth profiles also make possible to simultaneously increase the contact ratio and operating pressure angle beyond the conventional gears' limits. The main advantage of asymmetric gears is contact stress reduction on the drive flanks, resulting in higher torque density (load capacity per gear size). Another important advantage is possibility to design the coast flanks and fillet independently from the drive flanks, managing tooth stiffness and load sharing while keeping a desirable pressure angle and contact ratio on the drive profiles. This allows reducing gear noise and vibration level.

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

Tooth fillet profile optimisation

The tooth fillet design begins when the involute flank parameters are completely defined. The initial fillet profile is a trajectory of the mating gear tooth tip in the tight (zero backlash) mesh. The fillet optimisation process utilises three methods: random search method locating fillet points; trigonometric functions for fillet profile approximation; and FEA for stress calculation.

The first and the last fillet profile points of the initial fillet profile lay on the form diameter circles and cannot be moved during an optimisation process. The random search method is used to move the fillet finite element nodes along the beams that connect the fillet centre and the nodes of the initial fillet profile.

The bending stresses are calculated for every new fillet profile points' combination. If the maximum bending stress is reduced the program continues searching in the same direction, if not it steps back and starts searching the different direction. After the given number of iteration steps the optimisation process is stopped resulting with the optimised fillet profile that provides minimum bending stress concentration.

这种设计方法被开发用于渐开线齿轮并基于E B Vulgakov教授创造的通用参数原理，可定义为应用从动齿轮驱动开发过程，主要强调性能最大化和成本效益，而不考虑任何预定的加工参数。

齿轮齿和啮合综合

不需要基本齿条来确定齿轮齿的齿形。一个基圆(或两个不同的基圆，如果是非对称齿轮)的两条渐开线、其间的圆弧距离和齿顶圆对齿轮齿做了描述。均匀间隔齿构成了齿轮。齿间的填充剂不和啮合齿轮齿接触。但是，齿形的比例是关键，因为这是最大弯曲应力集中的区域。

在风力涡轮机变速箱中，在一个驱动齿侧面上的轮齿负载高得多，并且比对侧的非工作齿施加更长时间的负载。一个非对称齿形反应这种功能性差异。非对称齿轮齿的设计意图是以对侧非工作齿齿形的性能为代价来改进主驱动齿形的性能。在相对短的工作期间，非工作齿齿形被卸载或轻度加载。非对称齿形也可能同时提高啮合系数和实际压力角到超过传统齿轮的极限。非对称齿轮的主要优点是驱动齿侧面的接触应力降低，导致更高的扭矩密度(每个齿轮尺寸的负载容量)。另一个重要优点是可能独立于驱动齿侧面、管理齿刚度和负载分配设计非工作齿侧面和填充剂，同时在驱动齿形上

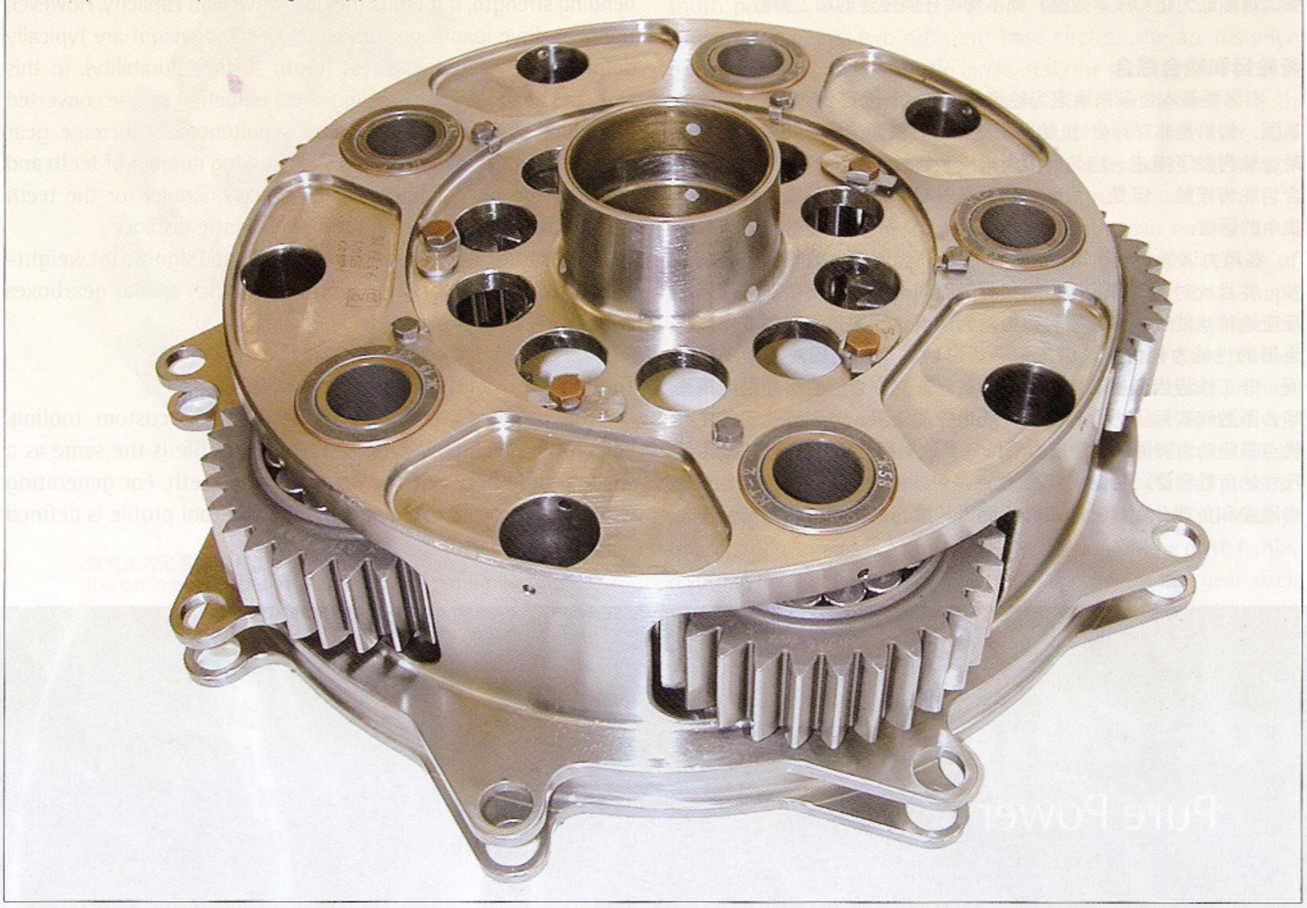
The 20-25 per cent bending stress reduction provided by the fillet profile optimisation can be used directly to increase the tooth bending strength, if it limits the gear dríve load capacity. However, the gear drive load capacity and its size and weight are typically defined by the contact stress (tooth surface durability). In this case, the benefit of the bending stress reduction can be converted to reduce the contact stress and simultaneously increase gear mesh efficiency. This is possible by increasing number of teeth and applying the finer diametral pitch (lesser module) for the teeth with optimised filler, keeping the given centre distance.

Application of asymmetric gears allowed significant weight-output torque reduction in comparison with similar gearboxes with conventional symmetric gears.

Tooling for directly designed gears

The optimised gear profiles require the custom tooling. For profile machining process the tool profile is the same as a space profile between the neighbouring teeth. For generating machining process like gear hobbing the tool profile is defined

非对称齿轮应用的例子
Example of the asymmetric gear application



保持一个想要的压力角和啮合系数。这有助于降低齿轮噪音和振动水平。

非对称齿使同时提高横向啮合系数和实际压力角超过传统齿轮极限值成为可能。

最优化齿填充剂齿形

当渐开线齿侧面参数完全确定时，开始设计齿填充剂。最初的填充剂齿形是精密啮合（零齿隙）中的啮合齿轮齿尖的一个轨道。最

相比这些创新，几乎所有变速箱的齿轮齿几何量看起来都很过时

by reverse generation, when the designed gear forms the tooling rack profile. The rack profile (pressure) angles, in this case, are selected to provide the best machining conditions.

Summary

Unlike the traditional gear design that is based on the rack generating process and driven by manufacturing convenience, Direct Gear Design is driven entirely by application requirements, when technical and market performance of product is critical. It provides ultimate optimised gear geometry solutions for custom gear transmissions such as the wind turbine gearboxes. Benefits of this approach include: higher load capacity; reduced size and weight; extended lifetime; reduced noise and vibration; higher efficiency; higher reliability; and reduced cost. ■

This article was written by Dr. Alexander L Kapelevich, a founder of the consulting firm AKGears, LLC, developer of the Direct Gear Design method and software

在风力涡轮机变速箱中，在一个驱动齿侧面上的轮齿负载高得多，并且比对侧的非工作齿施加更长时间的负载

优化填充剂使用三种方法：定位填充剂点的任意搜索法、用于填充剂齿形近似值的三角函数、用于应力计算的FEA。

最初圆角齿形的第一个和最后一个圆角齿形点位于成形直径圆上，在最优化法中不能被去除。任意搜索法被用于移动沿连接圆角中心和最初圆角齿形节点的连杆的圆角有限元节点。

计算弯曲应力以用于结合每一个新的填充剂齿形点。如果最大弯曲应力降低，这个程序继续在相同方向上搜索，如不，其回退并开始在不同方向上搜索。在给出迭代步的数量后，最优化法停止，获得最优化填充剂齿形，其提供最小弯曲应力集中。

如果齿弯曲强度限制了齿轮驱动负载容量，填充剂齿形优化提供的减小了20-25%的弯曲应力可被直接用于提高齿弯曲强度。但是，齿轮驱动负载容量及其尺寸和重量通常是由接触面应力（齿面耐久性）来确定的。如果这样，弯曲应力降低的好处可被转化为降低接触应力和同时提高齿轮啮合效率。这可能由增加齿的数量和将更小的齿轮节距（更低的模数）应用到带有优化圆角的齿上，保持给定的中心距来实现。

和带有传统对称式齿轮的类似变速箱相比，非对称齿轮的应用允许重量-输出扭矩极大降低。

直接设计齿轮的工装

优化齿形要求顾客工装。对于型面加工，齿形和邻近齿之间的间距是相同的。当设计齿轮形成工装齿条齿形时，为产生加工过程，如滚齿，齿形被反向产生定义。这个例子中，选择了齿条齿形（压力）角来提供最佳加工条件。

小结

和传统的齿轮设计基于齿条滚此法和由制造便利驱动不同，当技术和产品的市场性能成为关键因素时，直接设计法完全由应用要求驱动。它提供了最终的优化齿轮几何量解决方案，用于顾客定制的齿轮传动，例如风力涡轮机变速箱。这种方法的好处包括：更高的负载容量、更小的尺寸和重量、更长的使用寿命、更低的噪音和振动、更高的效率、更高的可靠性及更低的成本。

本文由Alexander L Kapelevich博士编写，他是咨询事务所AKGears有限公司的创始人，直接齿轮设计法和软件的开发商