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Gear Optimizing with Advanced Calculation Method

Development of the Gear Technology

All over the world, more and more gears are manufactured by injection moulding with plastic, sintering using metallic powders or through shaped grinding of the steel or by the gashing method. Therefore, several restrictions can be omitted which occur when the gears are produced by the hob method or conventional gear grinding methods. New possibilities open up for the optimisation of the gear with regard to operating noise, meshing and strength characteristics. With the support of suitable software, the calculation and optimisation of such gears can be done without any problems. That opens new horizons to improve gears.

The following tendencies will be more pronounced in the future:

- Metals will be increasingly substituted by plastics
- Significant reductions in gear noise and vibration
- Increase of the performance density (smaller models for same performance)
- Use of special tooth forms (non-involute toothing)

Procedures and calculation programmes for such optimisation of gears are the subject of this article.

Optimising of Tooth Form for Best Performance

Depending on the planned use, the requirements on the gear design can be very different: Low noise generation or vibration inducement, low manufacturing costs, highest strength and optimum service life are a few of the important criteria. In order to obtain these properties, several possibilities for the optimisation of the gears are available. These are described in the following sections. These methods are not new; but based on the improved possibilities in current manufacturing, several of them can be employed more frequently without (or only with a modest) increase in the production costs.

Different Optimising Procedures for the Tooth Form

Depending on the manufacturing procedure one or more optimising methods can be applied for the improvement of the gear characteristics. The different methods are:

Step 1: Geometry Change by given Reference Profile:
The geometry change through the variation of the module, pressure angle, helix angle and addendum modification with a given reference profile has a strong influence on the properties of the toothing. An optimum solution can already be found in this way for most cases, especially for angular helix gears. The fine drafting of the KISSsoft programmes (see below), can be used as an efficient software tool. These programmes compile all possible solutions for the given problems and classify them according to the specified targets (noise generation, strength, service life, ...). On this basis the engineer can choose the best suited solution to the specific problem. For example, with this method the strength can be increased by 20 to 25% using the same axis distance and tooth width.

Step 2: Geometry Change through Reference Profile Variation:

The reference profile change (usually an increase of the tooth depth) results in a change of the transverse contact ratio. For noise reduction and even-running toothings, a transverse contact ratio of 2.0 (or higher) is to prefer. The stiffness jump from the change of the single contact to the double contact can be minimised in this way. The transverse contact ratio can be achieved through a corresponding reference profile, but usually contact interferences occur by the total contact ratio of the gears. To solve this problem efficiently, the KISSsoft fine drafting module mentioned above offers an option which can find all possible solutions for a given nominal transverse contact ratio.

Step 3: Elimination of the Initial Impact though Profile Correction:
During the contact of a pair of gear wheels, the initial impact occurs when the two newly-engaging teeth have initial contact with each other. This impact generates noise and is more prominent with less accurate base-pitch and when the deformation of the tooth under load increases. Therefore, with plastic gears the involute at the tip is modified by an entry-curve. For gears made of metallic materials, the modification is termed as profile correction at the tip; due to the higher stiffness of the material, this correction is much smaller than with plastic gears. Usually the entry-curve is carried out on the tip on both wheels; however, as a variant (e.g. with rack gears) this correction is done only on one wheel, but then at the tip and the root. The entry-curve preferably consists of three narrowing arcs, integrated them into the tooth form (Figure 0-1), which KISSsoft computes if necessary.

Step 4: Optimising of the Tooth Root:
The safety factor against fatigue fracture increases considerably when the radius in the transition zone of the involute in the root circle is substantially widened. By the manufacturing of gears with the hob method, even with a well rounded tool, an optimum rounding at the foot is not always achieved. The safety can be substantially improved through a sophisticated modification, which has to be done under the used involute area (Figure 0-1). Through the gear stress analysis the improvement can be directly checked.

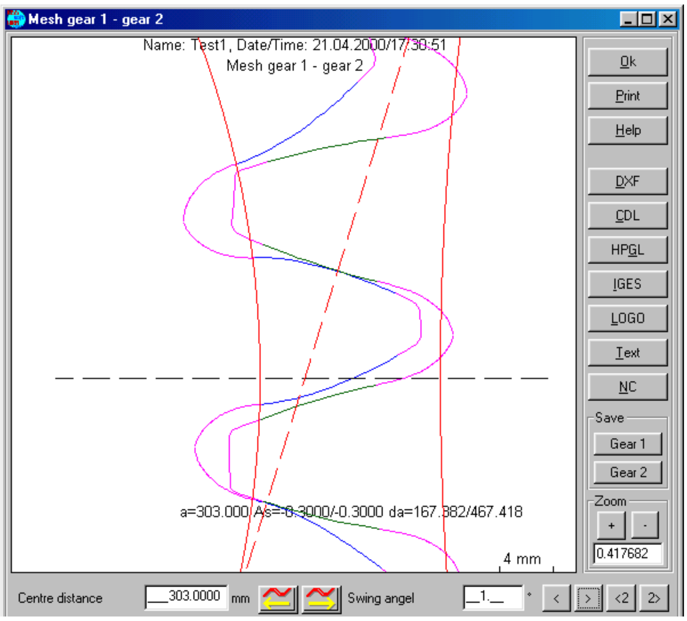


Figure 0-1 Control of the tooth-meshing of a modified gear pair (the modified parts of the contour are highlighted by colours).

Summary:
The optimisation measures have to be chosen under the consideration of the manufacturing method and the planned production numbers. Table 0-1 gives an overview of the manufacturing procedures and the optimisation methods. In order to design an optimal performing and inexpensive gear it is of importance to consider this.

Manufacturing Method	Material	Batch number	Tool	Optimisation level
Hob milling (only milling)	Metal	small	A	1
		middle	B	1, 2
		large	C	1, 2, 3, 4
	Plastic	small	A	1
		middle	B	1, 2
Hob milling and grinding	Metal	small	A	1, 3
		middle	B	1, 2, 3
		large	C	1, 2, 3, 4
Sintering	Metal	large	D	1, 2, 3, 4
Injection moulding	Plastic	large	D	1, 2, 3, 4
Shape grinding	Metal	middle/large	D	1, 2, 3, 4

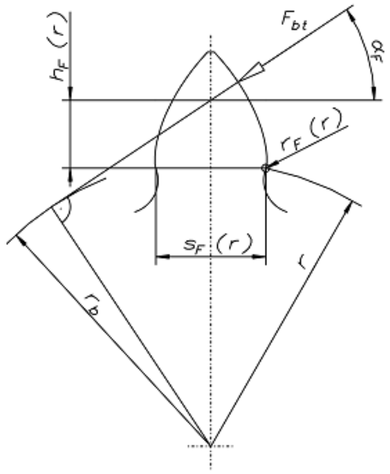
Table 0-1 Gear manufacture procedures and their suitable optimisation methods

Explanations to tools:

A: The existing manufacturing tool has to be used and therefore the reference profile is given.
B: For a medium sized number of pieces, an available tool can be obtained. Therefore the reference profile can be varied within certain limits (according to the standard tools).
C: For a large series, expensive tools especially designed for the optimised toothing can be bought.
D: For the manufacturing with sinter or injection moulding, the corresponding tools have to be made specifically. Therefore, the tooth form can be modified to obtain optimum operating characteristics without any extra costs.

Gear Stress Analysis for Optimised Involute Tooth Forms

A reliable algorithm was developed for the strength calculation of optimised gears. All normal calculation procedures determine the stress in the tooth root via a simplified model of the real conditions. According to ISO 6336, the critical cross section in the tooth root can be found via the 30° tangent of the root contour. According to AGMA, the Louis parabola is fitted to the tooth form, where the point of contact of the parabola with the tooth root rounding determines the critical cross section. Depending on the actual shape of the tooth root rounding, a more or less greater error is implied. In the publication of B. Obsieger a few years ago, a substantially improved calculation method was proposed. Based on the actual tooth form, the tooth form factor (ISO:YF, AGMA:Y) and the stress correction factor (ISO:YS, AGMA:Kf) are calculated at each point in the tooth root area and subsequently the location of the maximum of the product (ISO:YF*YS, AGMA: Y/Kf) is determined see the following figure.



$$Y_F(r) = \frac{6 * h_F(r) * \cos(\alpha_F)}{(s_F(r))^2 * \cos(\alpha_n)}$$

$$q_s = 0{,}5 * s_F(r) / r_F(r)$$

$$a = 1{,}2 + 0{,}13\,(s_F(r) / h_F(r))$$

$$b = 1{,}21 + 2{,}3 / (s_F(r) / h_F(r))$$

$$Y_S(r) = a * q_s^{(1/b)}$$

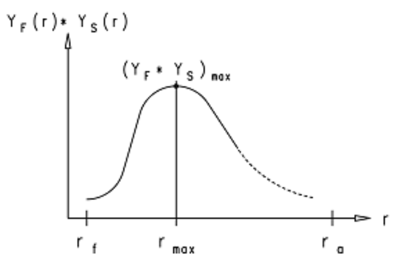


Figure 0-1 Derivation of the tooth root stress at any location of the root between YF(r) and YS(r)

This calculation procedure is integrated into the KISSsoft software. The critical tooth root cross section can be determined based either on the force application on the tip (AGMA: Loaded at tip), or the force application at the single point of action (AGMA: Loaded at PSTC). The strength calculation according to ISO, AGMA or DIN is then completely performed using these specific data. The course of the stresses can also be graphically shown, see figure below. The computation of the Hertian-pressure along the tooth flank is also calculated based on the actual tooth form. For each point of action the corresponding radii of curvature are determined for both gears and starting from this the pressure is computed. With the same data, the calculation of the sliding speed (Figure 0-1) is possible as well as the computation of the local contact temperature, the efficiency and the safety against scoring of any gear pair.

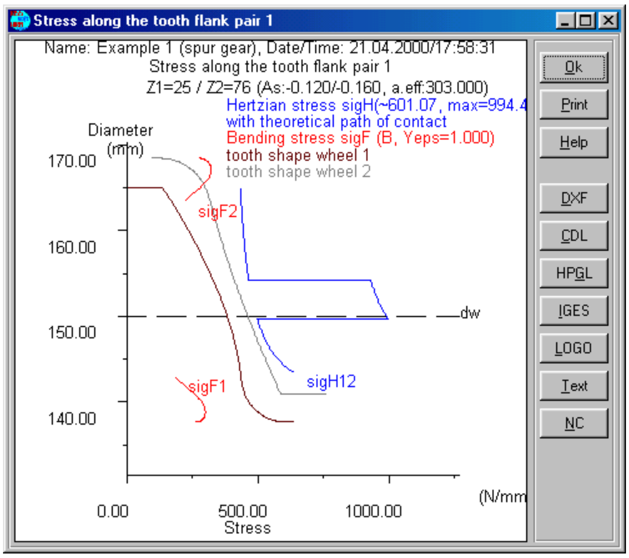


Figure 0-2 Tooth root stresses (and Hertian-pressure), calculated on the base of the actual tooth form and the meshing conditions.

Gear Stress Analysis for Optimised Non-involute Tooth Forms

The algorithms described in Chapter 2.2. are derived from the basic requirement of a gear tooth system and can therefore also be used for modified involute and non-involute tooth forms. Due to the direct incorporation of these special tooth forms into the software, comparative calculations between involute and non-involute tooth forms can be carried out very easily and quickly. As an example in a gear pump for a motor sport vehicle, the weight of the gear could be substantially reduced by replacing involute-gears made of aluminium by a cycloid made of plastic. Due to the optimum curvature of the cycloids (Fig. 4), the Hertian-pressure and sliding speeds could be reduced by up to 50% (especially in the critical zones at the tip and the root)!

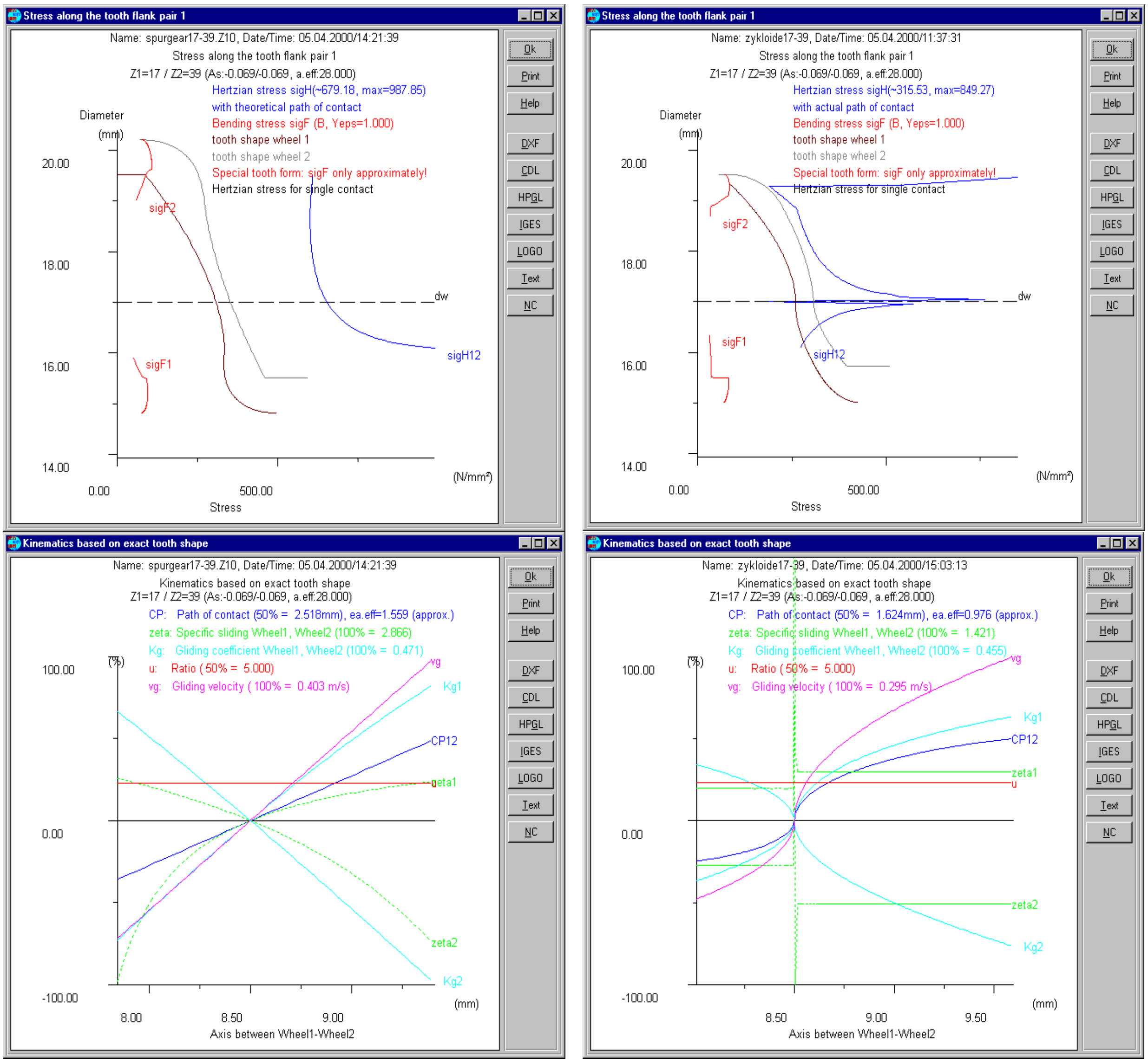


Figure 0-1 Comparison between the Hertian-pressure and the kinematic conditions of an involute gear with a cycloid wheel pair (number of teeth 17 : 39)

2.4 Tooth Meshing Stiffness

The variation of the tooth pair stiffness during a meshing cycle is a well known source for the generation of vibrations and noise. A procedure is implemented in KISSsoft which determines the meshing stiffness:

1. The exact tooth form is calculated (by simulating the manufacturing process with the cutter data);
2. For every position of the two teeth during a meshing cycle, the single tooth stiffness is determined.
3. By superposing the single stiffness of all teeth in contact, the overall stiffness is found (figure 5).

This very complex calculation is also integrated into the optimising procedure (Step 1 and 2 above). Therefore, for every checked solution, the variation of mesh stiffness will be displayed. If vibration reduction is very important, then a solution with lowest possible stiffness variation should be selected.

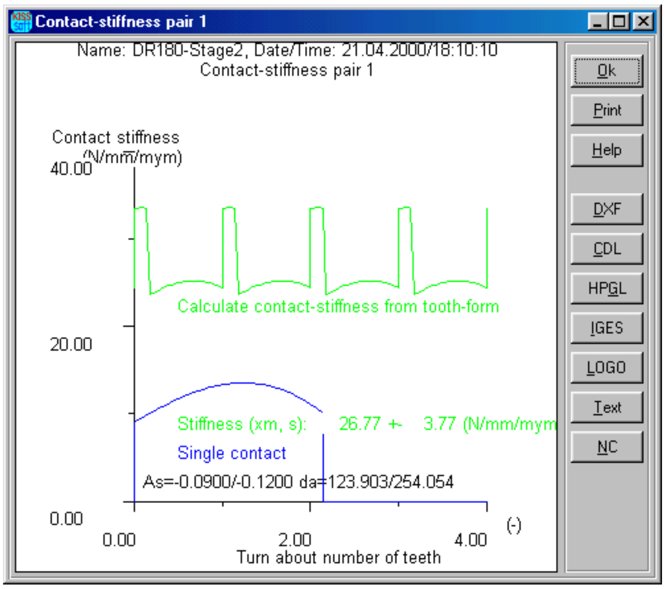


Figure 0-2 Tooth pair meshing stiffness of a deep tooth profile gear

Gear analysis and optimisation with KISSsoft

KISSsoft is a comprehensive software package for mechanical engineering. Besides modules for the analysis of Shafts, Axles, Beams, Roller- and Journal-bearings, there are modules for Screws and Shaft Hub connections such as Feather Keys and Splines. This software has been developed since 1985 by a Gearbox Manufacturer and has been used in its own engineering department for the design of gear drives. The software has consequently been released, and is used world-wide in over 300 companies.

The section on gear analysis is worth special mention, since it covers the complete area of this field of engineering, including non-involute tooth forms for special purposes. The gear analysis is especially comprehensive, incorporating the analysis of helical gears as well as bevel, worm and cross-helical ones. The gears can be in pairs, as epicyclical gears, or as stages with up to four wheels and racks.
The analysis of cylindrical gears is very flexible to allow the specialist to employ any possibility for the detailed sizing and design of a gear. Due to the clever design of the user interface of KISSsoft - with differentiates inputs into mandatory and optional inputs - the software is user friendly for all levels of engineering.
The calculation of the tooth geometry (with all the control measures and tolerances), as well as the complete stress analysis, is integrated into one program. This is important in investigating different solutions in the shortest possible time; if no stress analysis is required, this option can simply be deactivated.
Another feature worth mentioning is the visualisation of the gear-pairs: with a click of the mouse the shape of the gears is calculated to an accuracy of $1x10^{-4}$ mm by simulating the manufacturing process.
Besides the simple input of parameters, most of the critical values come with an interactive help for the required input, e.g. the addendum modification. The proposals for the addendum modification presents different solutions: an optimised value for high speed gears, the value for balanced specific gliding and more. The sizing function (in the definition of the reference profile) can be used to give the required profile height for the required contact ratio (e.g. deep tooth forms).

Gear Stress Analysis with Different Methods

Different calculation methods are integrated into this software which can be changed during execution of the program. The strength of the gear can be analysed according to AGMA2001, ISO6336 and DIN3990 without any additional effort. For gears made from plastics, which cannot be analysed with the above methods, special calculation procedures (such as the German VDI2545 and others) are also implemented. For any company planning to switch from an older standard to the new ISO6336, it is essential to have a tool at hand which allows the smoothest change possible, or even better, which gives the user the flexibility to work with the calculation method familiar to customers.

Additional Analysis Options

Besides the classical analysis functions, sizing and optimisation routines described above, the program has been developed substantially since its first edition in 1985.
For example, it is possible to obtain a proposal for the hardening depth for case hardened or nitride steels, based on the hoop stress (perpendicular to the tooth surface, Figure 6). Depending on the curvature of the flanks it is possible to optimise the heating time, hence reducing costs.
For plastic or sintered gears, the shape of the mould can be determined. This function takes into account the shrinking of the gears and can also optimise the tooth profile for the high pitch error usually encountered in moulded gears.
Additionally, the calculation can be conducted using equivalent design loads, which are freely definable or based on default time-load distributions.

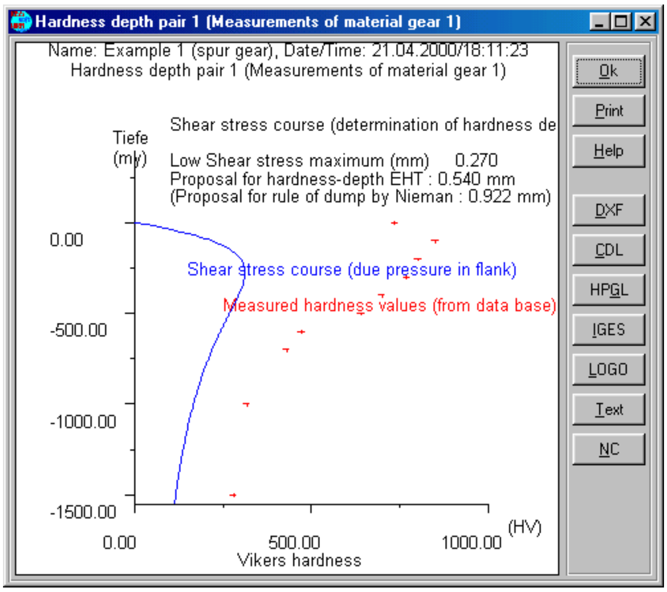


Figure 0-1 Determination of the hardness depth (Hoop stress perpendicular to the tooth surface, points of hardness measurements)

Optimisation of Gears

One of the main features of the software package is its ability to size and optimise machine parts to match a given load. In the gear module, the sizing can be used to obtain the complete parameters of a new set of gears based on the load and the nominal margin of safety.
The main parameters and ratios (such as width to diameter) can be defined as intervals, which leads to optimal engineering solutions. The sizing function will give a specific proposal with centre distance, tooth width, module and tooth numbers. The proposal will exactly fulfil the demanded minimal safety coefficients.
The optimisation function can be used to obtain the best performance of a set of gears based on the boundary conditions. One of the most common applications of this function is to optimise a set of gears to a given centre distance and face width for strength and noise. This is the type of problem for which the optimisation has been developed. The results of the analysis are a list of all possible geometrical solutions matching the boundary conditions. All the solutions are analysed completely and their properties are described in terms of strength, deviation of nominal ratio, contact ratio, efficiency, specific gliding, weight and inertia.

Summary

The performance of gears can nowadays be substantially increased and the noise generation reduced. With the use of specialised, user-friendly software these optimisations can be done by the research engineer within a short period of time. Furthermore, the manufacturing cost can be additionally reduced through smaller gear sizes.

[1] KISSsoft, Calculation Programmes for Machine Design, www.KISSsoft.ch.
[2] Obsieger, B.: Zahnformfaktoren von Aussen- und Innenverzahnungen, Konstruktion 32 (1980) S. 443-447.
[3] Kissling, U.: Noise and Vibration Reduction in cylindrical Gears by an accurate Optimising Procedure implemented in KISSsoft, Proceedings of the international gearing conference, Paris, 1999.