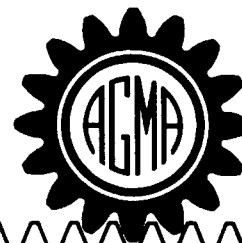


Cylindrical and Bevel Gear Inspection - A Simple Task Using Dedicated CNC-Controlled Gear Inspection Machines

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American Gear Manufacturers Association



TECHNICAL PAPER

Cylindrical and Bevel Gear Inspection - A Simple Task Using Dedicated CNC-Controlled Gear Inspection Machines

Guenter Mikoleizig, Klingelberg Soehne GmbH

[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Within the past few years, production conditions have changed considerably in many industrial enterprises. Increasingly small batch sizes must be produced to a high standard of quality in shorter time intervals. Consequently, the production equipment must be as flexible and simple to use as possible. The condition also applies for the production of gears. In this case, the function of the gear inspection technology is to check a wide range of gears, comparing them with tolerances predetermined in company standards or in national and international standards.

This task, very ambitious in itself, must frequently be performed under highly accurate production conditions. Suitable checking equipment is now available in the form of special CNC-controlled gear measuring machines, which have already been established in the industry for many years.

This presentation will describe the design and functioning of appropriate inspection machines. The conceptual design is explained in reference to the individual tasks, and the most important components of the testing machine, such as drive systems, probe systems, control and computer systems, are described. The second part of the presentation deals with software, as well as practical measurement examples in the areas of software management, operator guidance, evaluation and documentation of measuring results, examples of measurement times, measurement accuracy and the introduction of new software for the analytical evaluation of a cylindrical gear set. By means of the tooth contact analysis of a gear set, the combined effect of gear and pinion is simulated on the computer on the basis of individual profile and alignment measurements.

A particular challenge for gear inspection machines is checking of the flank form of spiral bevel gears. With these geometrically very complex shapes, different coordinates and a different master direction have to be taken into consideration for each measuring point. In conjunction with a special 3D-probe system, a special control function and the related evaluation, it is possible to achieve continuous recording of measured values with high measuring accuracy and short measuring times also on such workpieces.

The preparations for performing a measurement are supported by graphic operator guidance and can be carried out by the operator in just a few minutes.

When evaluating the measuring results, there is the requirement to derive the necessary condition of the bevel gear manufacturing system directly from this evaluation. In this connection, the presentation will discuss a new, fully-automatic correction system.

The presentation will illustrate the status and the potential of current gear inspection machines with practical examples.

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CYLINDRICAL- AND BEVEL GEAR INSPECTION

- A SIMPLE TASK USING DEDICATED CNC-CONTROLLED GEAR INSPECTION MACHINES -

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1.0 Introduction

As in many areas of industry, the prevailing conditions have changed in gear manufacture as well. Higher quality requirements and frequently changing batch sizes must be dealt with in production on a daily basis.

In this regard, the gear measuring technology undertakes the important task of checking and documenting the gears, which are as a rule modified and optimized, and specifying any necessary setting correction to production. In many cases, national, international and also company-specific standards must be complied with in this context.

Consequently, gear measuring technology is of great importance in achieving and subsequently maintaining a required quality standard.

The relevant gear inspection machines required to determine individual deviations on profile, lead, pitch and runout are dealt with below.

2.0 Basic design and function of gear measuring machines

CNC-controlled gear inspection machines have already been successfully used in the industry for many years. Starting from the known measuring tasks of profile, lead, pitch and runout on cylindrical gears, these machines offer a very much greater diversity of application on the basis of their technology. Ultimately, an extended software package is all that is required to also be able to inspect worms and wormgears, bevel gears or even gear cutting tools such as hobs, shaving and shaper cutters. Basically, CNC-inspection machines consist of the following components:

- Basic bed with rotational axis and linear measuring axes
- CNC-control for executing measuring movements and forming measured value
- Evaluation computer system for programming measuring runs and evaluating measurement results, including documentation via printer
- Evaluation software for inspecting a diverse range of gear-related workpieces, suited to the evaluation computer system

Figure 1 shows an overall view of a CNC-controlled inspection machine of medium structural size for workpieces up to 650 mm diameter.

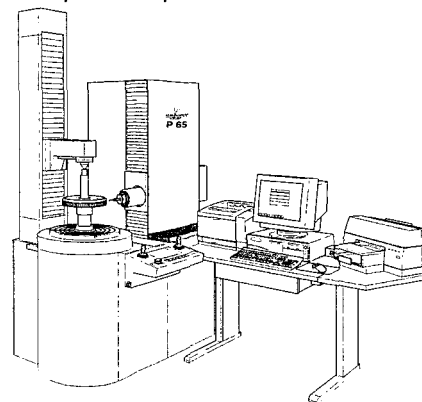


Figure 01: CNC-controlled Gear Inspection Machine

The components mentioned above can be easily identified. The functioning of a CNC machine is comparable to the functioning of a mechanically controlled inspection machine for cylindrical gear measurement. The generating principle of an involute is used during profile measurement similarly to Figure 2. Further parameters can also be checked on cylindrical gears by means of the coupled movement of other axes.

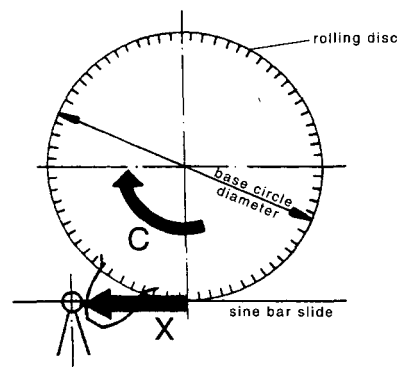


Figure 02: Profile measuring (involute generating principle)

In the case of a CNC-controlled inspection machine, instead of mechanical drive elements such as rolling disk and friction bar (Figure 2), electronically controlled individual drives are used on the axes. In other words, the mechanical gear is replaced by an electronic gear. The functional interrelationship is shown

in Figure 3, again in connection with profile inspection. The measuring movement for generating the involute form occurs through a coupled movement of rotational axis C including workpiece with the linear axis X and the mounted probe system. The coupling ratio (transmission ratio) depends on the technical data of the cylindrical gear to be inspected. In addition, each axis is equipped with an M1/M2 drive motor as well as the relevant angle/length measuring system.

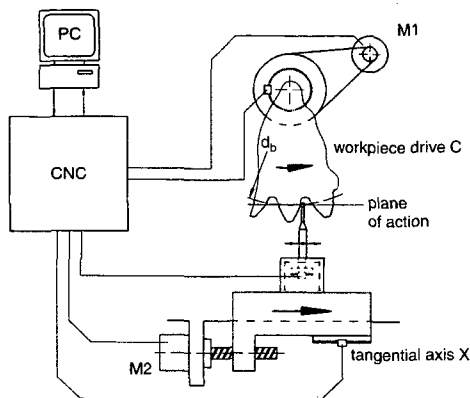


Figure 03: CNC-controlled Profile Measuring (principle)

The synchronization of the movement cycle is ensured by the CNC control. The probe system thus directly records the profile deviations of the test piece. Further representation and evaluation of the measuring curves subsequently occurs via a PC computer. The inspection cycle for lead measurement on cylindrical gears is generally the same, except that in this case a coupled measuring movement of axes C and Z (Figure 4) is executed in relation to the nominal lead (base helix angle β_b). Depending on the measuring task, diverse axial combinations can be implemented, both for continuous and for individual point probing.

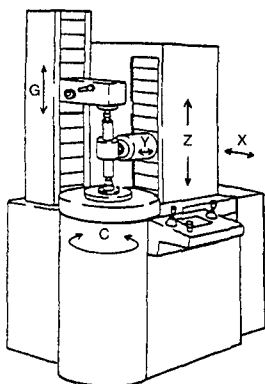


Figure 04: Axes of a CNC-controlled Gear Inspection Machine (Example)

2.1 Mechanical construction and probe system

The basic component of an inspection machine is the bed, which should be designed as compactly and rigidly as possible, so that it can also accept high workpiece weights without the overall geometry being affected. Gray cast iron has proven itself as the construction material, enabling reliable achievement of the above-mentioned properties. Other materials are also well proven.

The superstructures of the X, Y, Z-linear axes and the C-rotational axis are also made of cast iron, with fitted prestressed, backlash-free and highly accurate anti-friction guideways. In addition, the selected material combination guarantees a high geometrical resistance to the effects of temperature. In order to be able to avoid influences, fluctuations or noise when recording measured values, direct drives without mechanical drive elements have successfully become established, both for the rotary table (high-pole servomotor) and for the linear axes (linear motor), in addition to conventional drives, e.g. via friction gears or ball screws.

A further unit is a column with tailstock (G-axis, Figure 4) which is located on the basic body for vertical workpiece mounting between centers. The tailstock can be manually or mechanically adjustable, depending on the adjustment range.

The probe system provided is of particular importance on a gear inspection machine. According to Figure 4, this system is located at the front end of the Y-axis. Three-dimensional probe systems, as shown in Figure 5, provide better prerequisites for recording very different functional surfaces on gear-related workpieces in a single run.

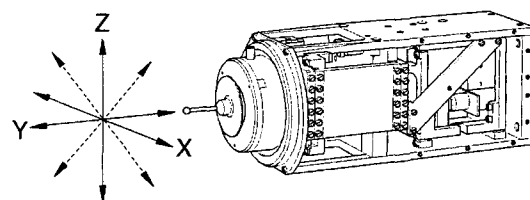


Figure 05: 3D-probe system

Measured values are recorded in the case of profile and lead measurements on cylindrical gears is performed by using the X-measuring axis of the probe system. In the case of lead measurements on cylindrical gears with a large helix angle or in the case of a lead measurement on a cylindrical worm, the probing direction can be continuously preselected in the X/Z-plane in accordance with the direction normal of the respective measuring point. This probing method

ensures a high probing accuracy. The Y-probing direction enables e.g. root and tip circle diameters to be recorded on cylindrical gears, as well as e.g. defined reference surfaces to determine the precise workpiece position.

In contrast to switching 3D-probe systems, which are particularly suitable for individual point probing, "measuring probe systems" are required for gear inspection for continuous measured value recording (scanning) e.g. in the case of profile and lead measurements. I.e. each measuring axis must have a large measuring path (e.g. 1 mm) and be equipped with an appropriate length measuring system.

In this regard a digital measuring system offers the advantage that the signals can be processed directly in the CNC control without conversion and the measuring accuracy remains constant, irrespective of the measuring path.

Another essential feature of a modern probe system is a probe element exchange device (Figure 6). Here the probe element is connected to a change plate. The connection to the actual probe system is provided by an adapter device with high centering accuracy. A similar device offers the advantage of probe element exchange without recalibration, as the calibration data already stored in the computer system of the inspection machine can be used.

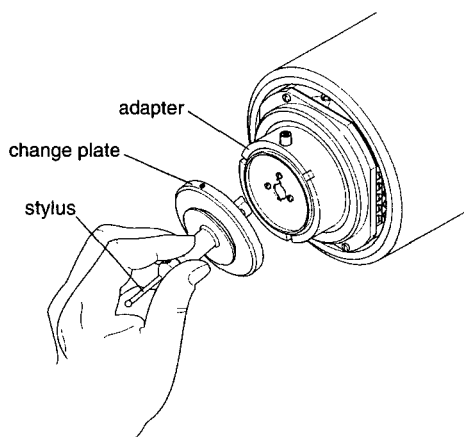


Figure 06: Probe changing device

Also particularly important are the protection systems in a probe system in the event of collision. These prevent downtimes of the entire device, as well as high repair costs.

2.2 Control and computer system

In addition to the mechanical components of an inspection machine, the control and computer system form the second essential component.

The CNC-measuring control performs all the inspection machine functions that are important for a measuring run. The schematic design of a control computer unit can be seen in Figure 7. Here the core elements are a rapid 4-axes motion controller equipped with microprocessors with a high clock frequency as well as a higher-level control computer for multiple axes interpolation and measured value recording. In conjunction with special control software, up to 4 measuring axes (X, Y, Z and C) can be linked together. The coupling can occur linearly or for any spatial curves in accordance with predetermined nominal data.

Further processing of measured values occurs in an evaluation computer, a standard commercial PC computer in a current design. The conception of the measuring movement generation and of the formation of measured values via the CNC control, on the one hand, and the presetting of the measuring run and processing of the measured values via PC computer on the other hand, guarantee high system reliability. To further increase availability, the control unit can also be equipped with a modem system. This allows remote diagnosis/remote update of evaluation software and control software.

The standard PC computer system used also opens up diverse options for data storage and documentation of measuring results via printer systems.

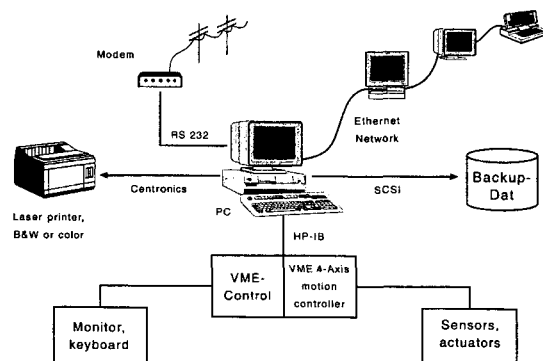


Figure 07: CNC control concept

It frequently occurs that several inspection machines are used simultaneously in production units. In this case, the machines can be networked together (Figure 8). If the computer unit of one inspection machine is set up as the server, then all inspection machines will have access to all workpiece data to be taken into account. Likewise, measuring results can be stored centrally. New workpiece data subsequently only need to be entered once and are then also available on all other machines. A further networking variant is the installation of an additional computer system. Thus new measuring programs can be prepared or existing measurement series can e.g. be statistically

evaluated externally, without blocking an inspection machine. Connection of the local network to a company-specific network for further processing of data

is, on principle, just as possible as networking with other production devices, e.g. gear grinding machines, provided that existing interfaces are coordinated with each other.

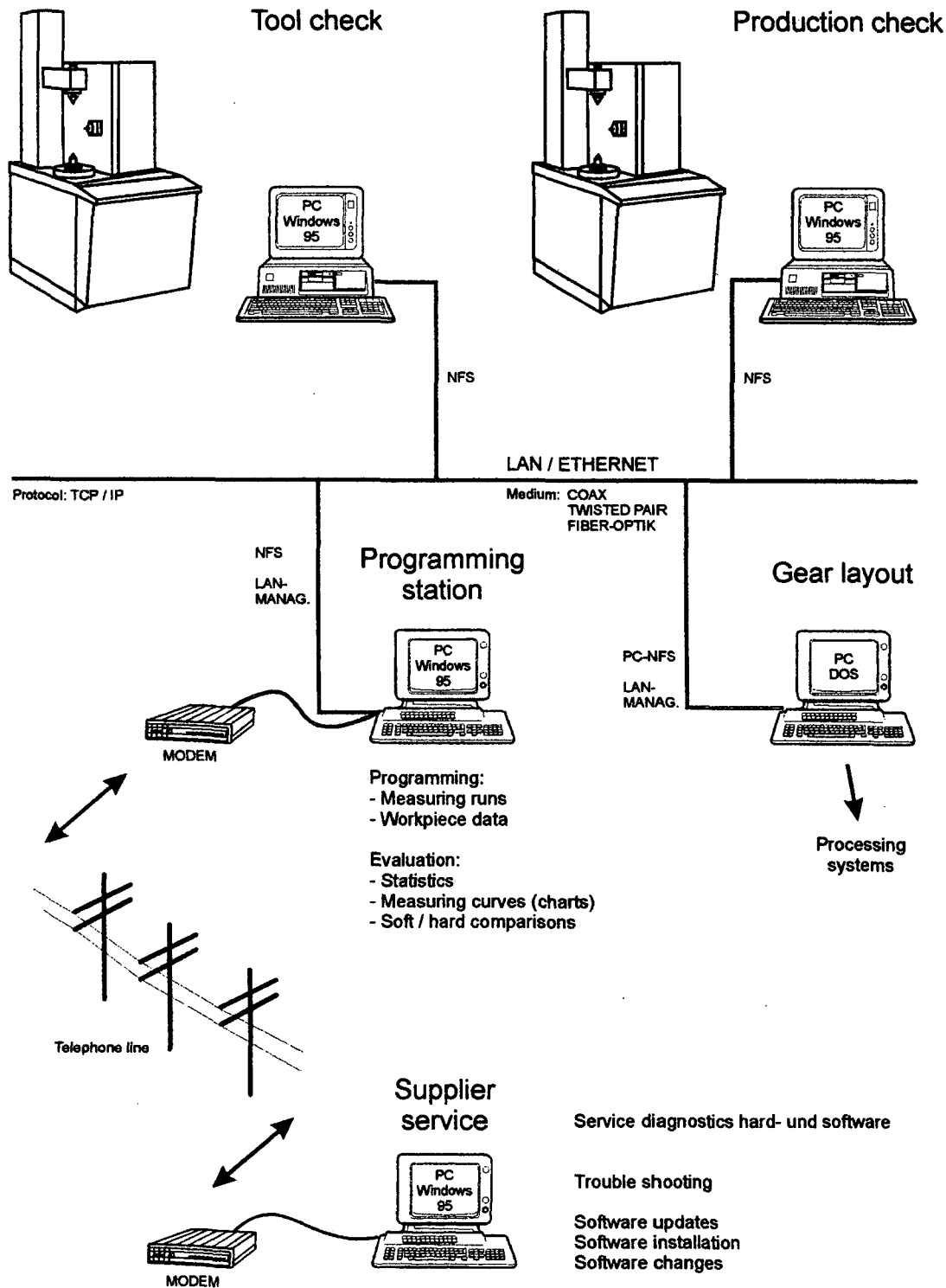


Figure 08: Network gear inspection machine

3.0 Preparation and performance of a cylindrical gear measurement

The interfaces between the inspection machine and the operator are formed by the evaluation computer, including software, for checking the individual gear-related workpieces or gear cutting tools.

The operator guidance for the programs (Figure 9) should be designed so that the required measuring run can be programmed in plain text without special programming language. Graphically supported operator guidance offers further advantages. When programming a run, all necessary entries/specifications are made, such as:

- Record data for the measurement, such as place of measurement, name of the operator, order no. etc.
- Gear data of the workpiece, such as module, number of teeth, pressure angle, helix angle etc.
- Type of evaluation, such as DIN / AGMA / ISO evaluation, tip relief, root relief etc.
- Measuring run selection, such as profile measurement, lead measurement, gear pitch etc.
- Selection of the diagram magnifications etc.

When programming is completed, the measuring run is stored in the computer under a workpiece ident. no.. In the case of repeat measurements, this run can be directly reactivated via a catalog of stored runs. A program change is thus possible within a few seconds.

The measuring run itself then proceeds fully automatically. If desired, a special probing routine also makes it possible to find a tooth gap automatically, provided that you do not wish to probe a precisely predefined tooth flank at first (Appendix 1).

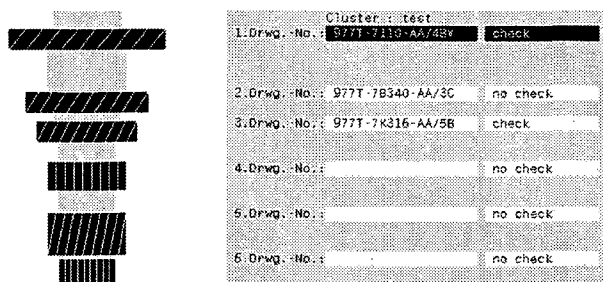


Figure 09: Operator guidance

With many measurements, it is necessary to first of all define the exact workpiece axis, due to inadequate clamping accuracy of the workpiece. In conjunction with a probe combination, as shown in Figure 10, the respective reference surfaces e.g. borehole, end face are probed, and only then the respective gear. In

conjunction with a special software package, radial and axial runout deviations up to 2 mm can thus be compensated. The gear itself can also be used as the basis for defining the workpiece axis under certain conditions (e.g. in the case of internal gears).

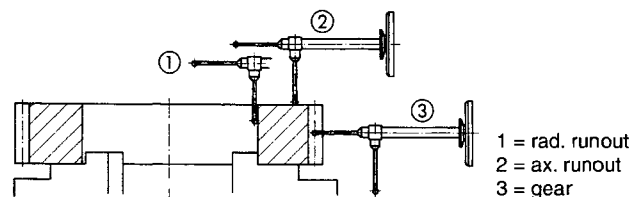


Figure 10: Definition workpiece axis

The measuring movements for profile and lead measurements have already been described under item 2.0.

The gear pitch measurement is performed as an absolute measurement. The probe element is inserted into the tooth gap via the Y-axis and alternately probes the left and right flank. During probing, the probe element is moved by a predetermined amount until it equals the nominal value of the measured value recording. Measured value recording then occurs via the angular measuring system on the C-rotational axis. The cumulative pitch error is thus determined immediately and the individual deviations are subsequently evaluated.

Like the individual deviations, the gear runout or dimension over two balls can also be determined from the cumulative pitch error.

Example 1 shows the results of a profile and lead measurement on a cylindrical gear. The top section of the measuring sheet (1a) contains all data for documentation of the measurement, as well as the technical data of the workpiece and inspection areas.

Section 1b shows the profile measuring charts on tooth 1, 4, 7, 10 left/right flank respectively, with tooth 1 having been inspected at three different places (bottom, middle, top) in the sense of a gear twist. Markings for the start and end of the evaluation area are drawn on the charts.

The comparison scales for the magnifications are shown on the left side of the measuring sheet. Other additional data are located in section 1b, e.g. the sine symbol, which means that the measurement has been performed with compensation of residual clamping errors. The comments coast/drive act as an aid for classifying the charts.

In the middle section (1c) of the measuring sheet, the permissible tolerances for the individual inspection parameters in accordance with DIN 3962 Quality 6

are shown. On the left and right of these are the actual values of the current measurement. The actual quality levels are also displayed here, as well as any tolerances exceeded (bold type or colored marking).

The charts for the lead measurement are generally displayed in section 1d. The comment VDI on the right means that the $\pm$ sign rule has been appropriately taken into consideration, in contrast to a rule in accordance with DIN standards. The designation N:Z inserted at the bottom of the sheet means that the evaluation parameters defined in the marked evaluation area have been extrapolated to the entire face width "b" (f_{hp} in accordance with DIN standard).

In contrast to the profile measurement, the lead measurement includes an evaluation with crowning (C_β). In the middle section 1e, a crowning tolerance $3 \pm 2 \mu\text{m}$ has been preset for the left flank and $2 - 7 \mu\text{m}$ for the right flank. The actual values with tolerance checking are also shown here for each measuring curve.

Example 2 shows the results of the pitch and runout measurements on the same cylindrical gear. In section 2a the results of the individual and cumulative pitch deviations are shown for the left/right flanks respectively.

In section 2b the tolerance comparison is then shown again. At the bottom of the measuring sheet, the dimension over two balls Mdk with the range over all teeth is also output on the right.

The measuring sheet printouts 3 and 4 can be used as an example of an evaluation in accordance with AGMA standard.

3.1 Tooth contact analysis on cylindrical gears

Modern automotive transmissions have to meet the requirements of high performance, low noise emissions and reduced costs (Figure 11). For the gears used in transmissions, this means that precisely defined features with low tolerances must be guaranteed in mass production.

The contact and running behavior of a gear are influenced by its design, including certain corrections and tolerances. The actual condition of the gear and mating gear and the resulting running behavior in terms of load and noise are decisive for the functioning of the gear. This is where the tooth contact analysis comes in.

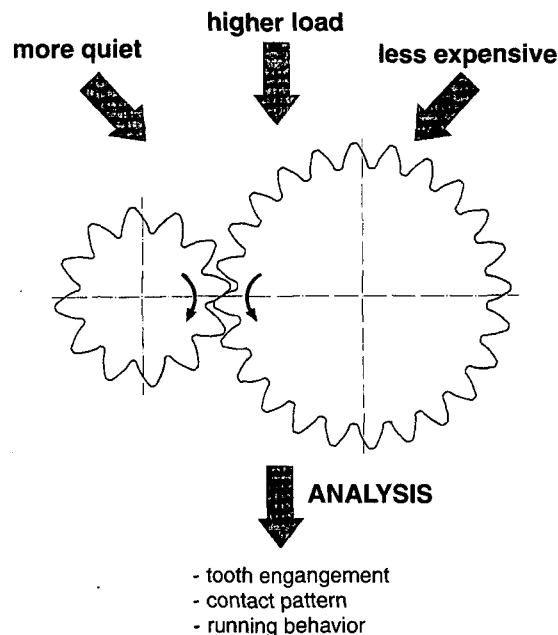


Figure 11: Gear train performances

The basic idea behind this software is to link the actual data for a gear obtained from individual measurements (profile and lead or topographical measurements) with the data for the mating gear in a computer and thus determine the resulting gear pattern, motion graph and ease-off topography. This means that information on a gear's contact and running behavior can be derived directly from the results of the individual measurement with no additional running tests. The measurement results of the distortion and topographical measurements form the basis for the "tooth contact analysis".

The distortion measurement contains 3 profile measurements relative to the gear width and 3 lead measurements (root, reference and tip circle, figure 12).

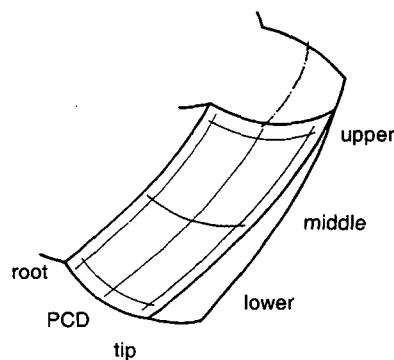


Figure 12: Distorsion measurements

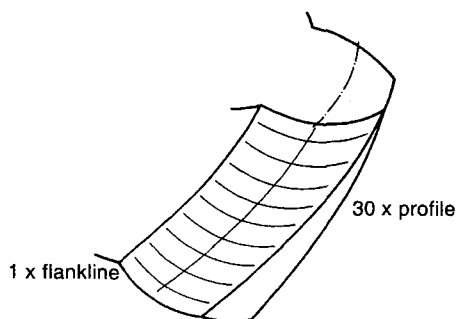


Figure 13: Topographical measurements

In the topographical measurement, up to 30 profile measurements are carried out with one lead measurement per flank (figure 13). The saved measurement results (max. 30 x 10 grid points) for the gears to be used are then evaluated by the "tooth contact analysis software" as follows (figure 14):

- Separate evaluation of both driving and coast-side flanks
- Deviation topography with deviation matrix
- Motion graph
- Contact pattern representation with preset contact pattern depth
- Evaluation (pairing) with master gear
- Simulation of axis-angle deviations

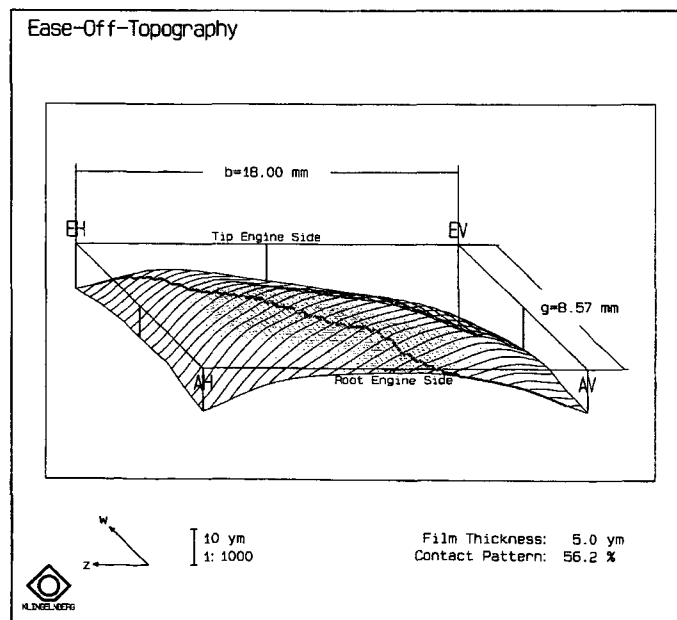
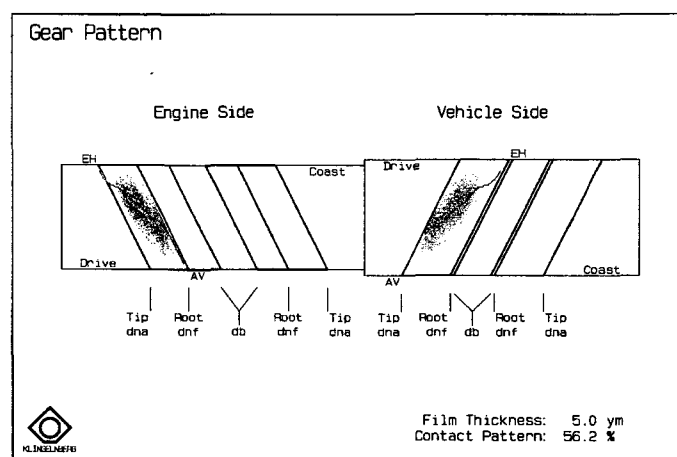
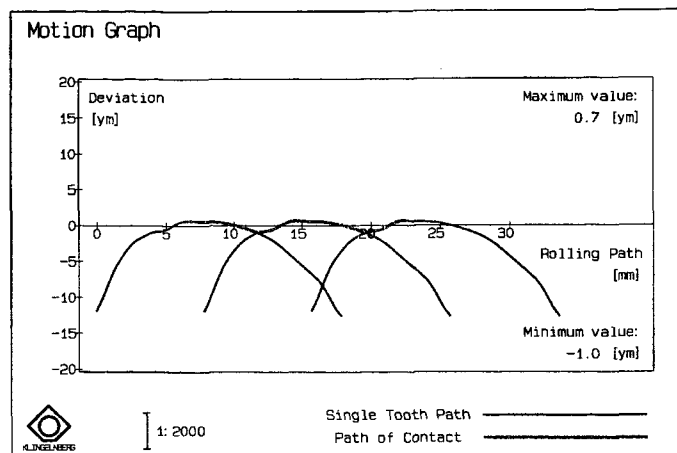


Figure 14: Evaluation tooth contact analysis