Checking Large Gears

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Reliable Measurement – A Necessity for Economic Production

Gear manufacturing schedules that provide both quality and economy are dependent on efficient quality control techniques with reliable measuring equipment. Given the multitude of possible gear deviations, which can be found only by systematic and detailed measuring of the gear teeth, adequate quality control systems are needed. This is especially true for large gears, on which remachining or rejected workpieces create very high costs. First, observation of the gears allows adjustment of the settings on the equipment right at the beginning of the process and helps to avoid unproductive working cycles. Second, the knowledge of deviations produced on the workpiece helps disclose chance inadequacies on the production side: e.g., faults in the machines and tools used, and provides an opportunity to remedy them.

Selection of Measuring Methods

The application for which a gear is intended and its specified quality grade will determine which checking method should be used. Certain checking methods cannot serve as reliable criteria for gear performance in all cases. The radial (double flank) composite deviation test, for instance, is not a suitable checking method for gear speed and torque transmission capacity or for gear noise. Furthermore, one measurement may be substituted for another; for example, the tangential composite test for the cumulative pitch measurement. Therefore, it is neither economic nor necessary to measure every different kind of defined gear deviation, such as, run-out, radial or tangential (single flank) composite deviation, single pitch, cumulative pitch, profile and helix deviation, undulation and surface roughness. Which of the inspection methods should be applied depends chiefly on the function of the gear, on its quality degree, and sometimes also on the manufacturing method by which the gear teeth were machined.

In many cases other conditions are imposed by special acceptance regulations or by the limitations of available inspection equipment. Many gear accuracy characteristics are related to the gear axis. Therefore, two important machining and checking prerequisites and sufficiently accurate reference faces for determining the axis can be determined. On large gears, they are usually represented either by two sufficiently distant radial reference cylinders; e.g., by the bearing surfaces, or one radial and one axial reference face. (Fig. 1)

Individual Pitch Checking

Relative measurement

Up to now, individual pitch accuracy of large gears has generally been checked by applying the chordal (relative) measurement. With this method, the length of chord between the two contact points on two consecutive corresponding flanks is measured. The individual pitch deviation arrived at by this method is the difference between the actual measured value and the mean value of all measurements taken around the circumference.

Testers used for chordal pitch measurement usually bring two feelers into the tooth spaces to exactly the same depth. The gear under inspection is slowly turned and the feelers are moved in and out in an appropriate rhythm. (Fig. 2)

Absolute measurement

New developments in improved angular decoder systems allow the introduction of angular (absolute) measurement for large gears. Measurement is performed by controlling the dividing angle via optical or electronic instruments, whereby the feeler senses the actual position of the flank. (Fig. 2) Angular measurement supplies the individual pitch deviation as the difference between the readings on two consecutive flanks, minus the theoretical pitch.

Control of Individual Pitch Accuracy by Base Pitch Checking

Under certain conditions, control of uniformity of normal base pitches is a substitute for transverse individual pitch checking. This auxiliary method, usually performed by using a hand instrument according to Fig. 3, should, however, only be applied when the gear has not been machined with a multitooth cutter or with a single thread hob or grinding wheel. Otherwise, measured values would basically show only the pitch accuracy of the tool, but not of the gear. (Fig. 4)

Base pitch measurement is independent of the gear axis; any eccentricity of the gear does not influence the recorded result. Therefore, and also because the two feelers do not contact identical flank points, the base pitch checking cannot serve for determining cumulative pitch deviations.

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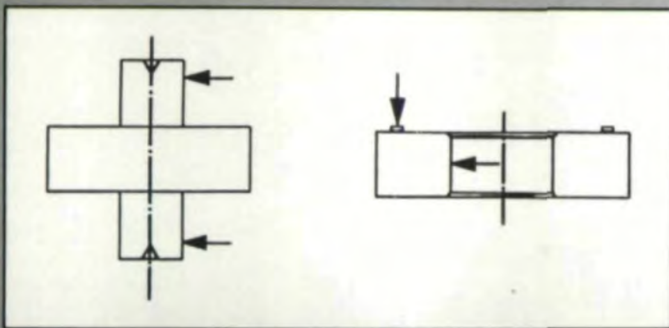

Fig. 1 – Definition of gear axis

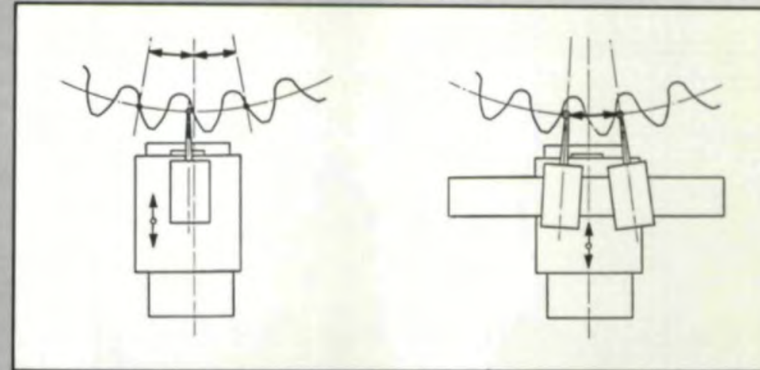

Fig. 2 – Relative and absolute individual pitch checking

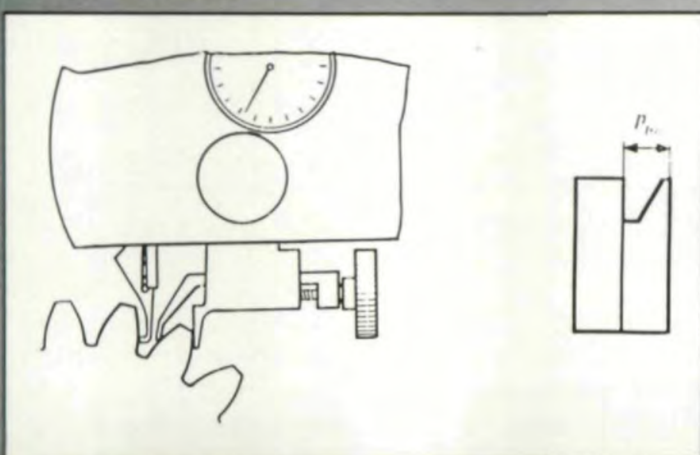

Fig. 3 – Base pitch measurement by hand instrument

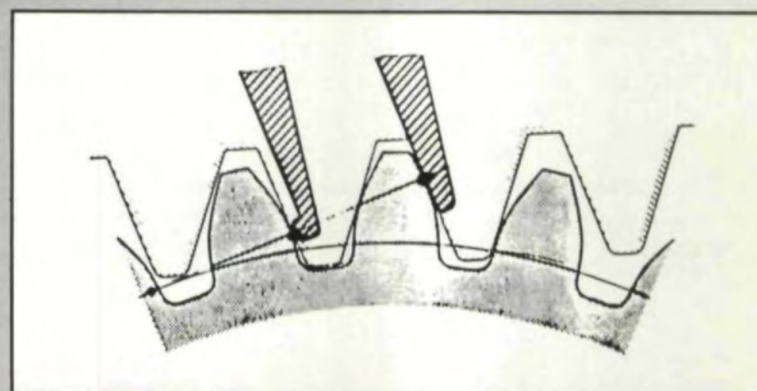

Fig. 4 – Identical simultaneous contact points on multi-tooth machining and on checking

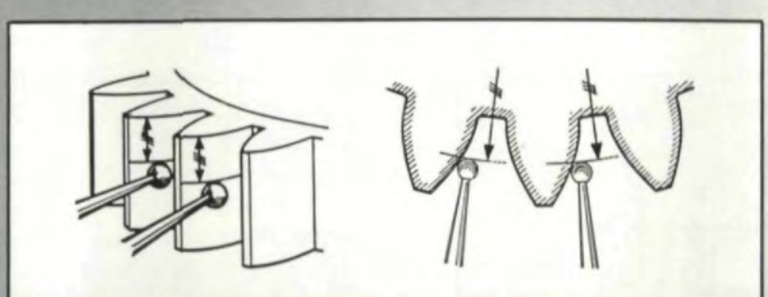

Fig. 5 – Setting of feelers for chordal (relative) pitch checking

Cumulative Pitch Checking

The cumulative pitch deviation between any two corresponding flanks can be determined by algebraic summation of the individual pitch deviations or of the span pitch deviations over the corresponding sector of circumference.

For determining the cumulative pitch deviation by chordal measurement, the two feelers must be set so that they contact as nearly as possible identical flank points at the moment when the reading is taken. (Fig. 5) This is in order to avoid accumulation of inadequacies of measurement due to irregular flank form and surface roughness. (Fig. 6)

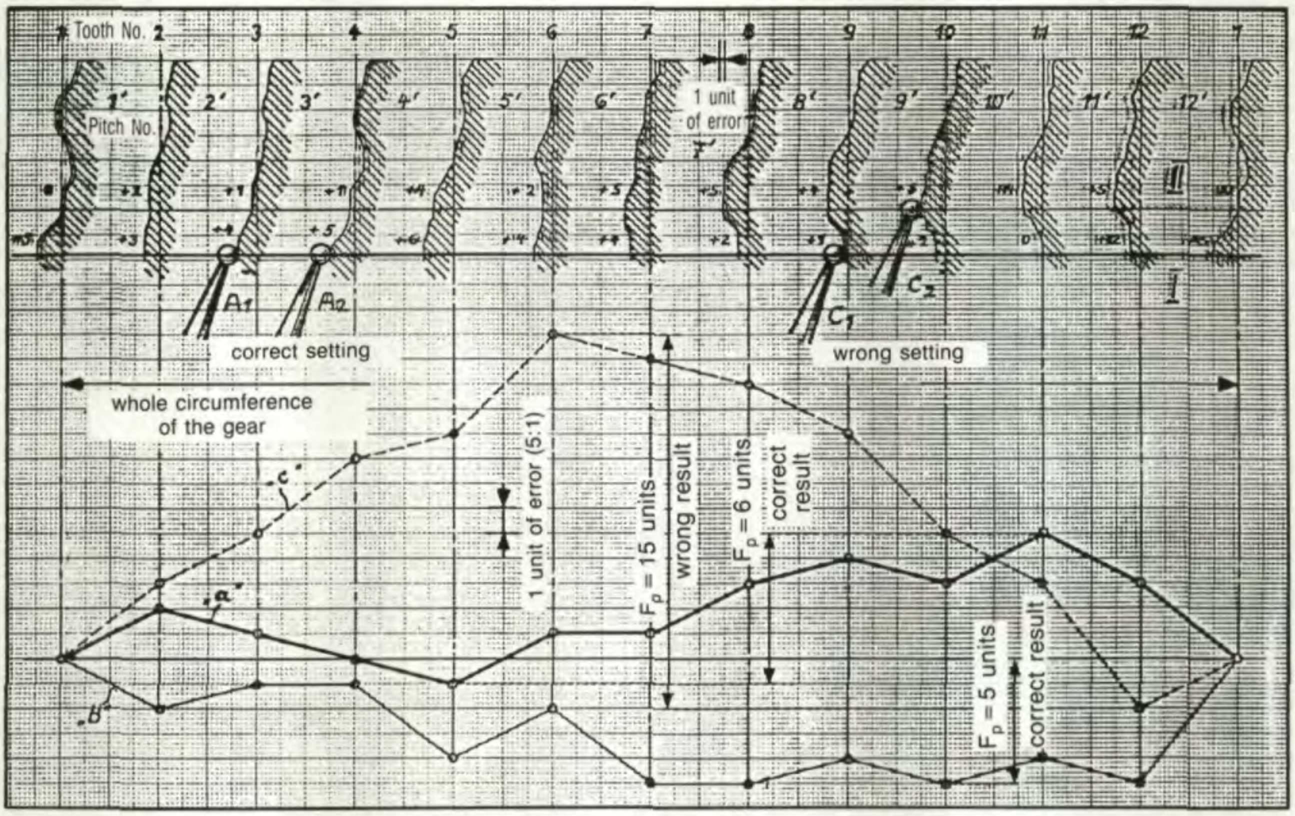

Fig. 6 – Wrong checking results due to incorrect setting of feelers

Fig. 6 illustrates the schematic situation. With the feelers set in correct (identical) radial positions, A1 and A2, (Plane I), curve "a" is established, and the total cumulative pitch deviation amounts to six units. In other correct settings; e.g., in Plane II, slightly different, but still correct, curves with a similar deviation (curve "b" with five units) would result. Results with different, but correct, probe settings can vary by the sum of the form deviations within the relevant part of both flanks.

If, however, the feelers are set incorrectly to different positions, C1 and C2, curve "c" is obtained, the measuring result showing a total cumulative pitch deviation of 15 units, which in reality does not exist.

When applying the angular measurement, the cumulative pitch deviation results directly as the difference between the two readings of angles at both ends of the arc considered, minus the theoretical angle of the corresponding sector. The angle values are converted to length values by multiplication by the pitch radius.

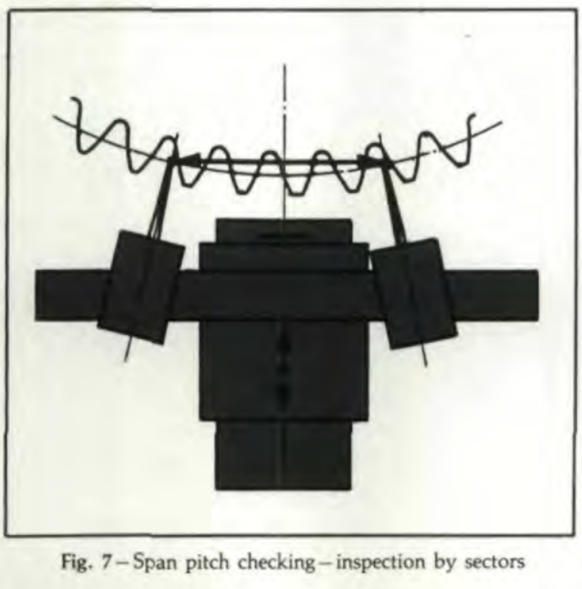

Fig. 7 – Span pitch checking – inspection by sectors

Inspection by Sectors, Span Pitch Checking

If the cumulative pitch deviations are to be determined from chordal individual pitch measurements, substantial measuring errors can occur in the case of gears with a large number of teeth. These measuring errors are caused by the possible summation of errors of the many individual readings and by inadequacies of measurement due to irregular flank form deviations when the two feelers do not contact exactly the same flank points.

In order to reduce the number of readings and, hence, the uncertainty in checking, the use of "span pitch checking" (Fig. 7) is recommended.

With this method, the cumulative pitch deviation is not determined on each individual pitch, but on successive sectors containing a certain number of pitches.

The number of pitches per span is selected as, for example, to supply a sufficient number of plot points for the cumulative pitch deviation curve. On the other hand, it is limited with respect to practical and feasible instruments. A practical guide to the number of pitches (S) per span is ex-

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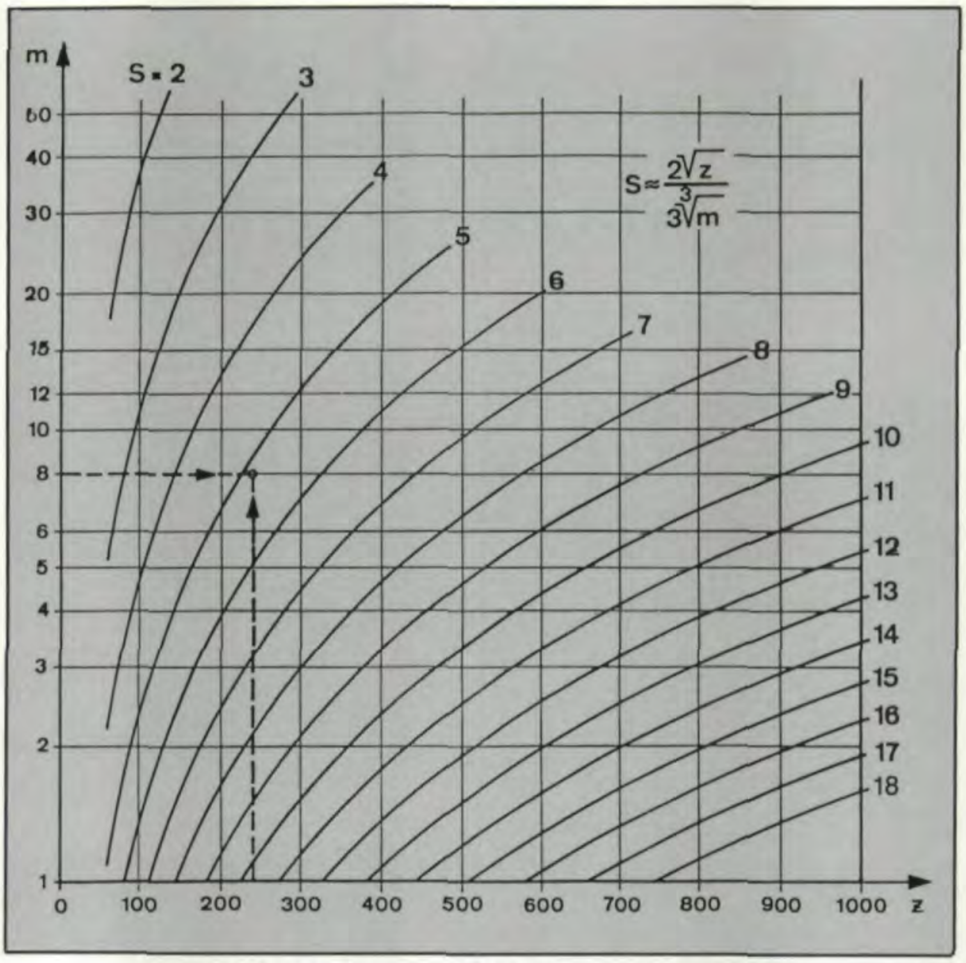

Fig. 8—Guide to the number (S) of pitches per span pitch checking

pressed by the formula and the diagram shown in Fig. 8. Nevertheless, the rules for setting the feelers must be observed.

Checking of Profile

Most testing instruments reveal the involute tooth profile by following the flank contour with a stylus and producing profile diagrams whereby the norminal involute is represented by a straight line. The diagram length is equal or, if magnified,

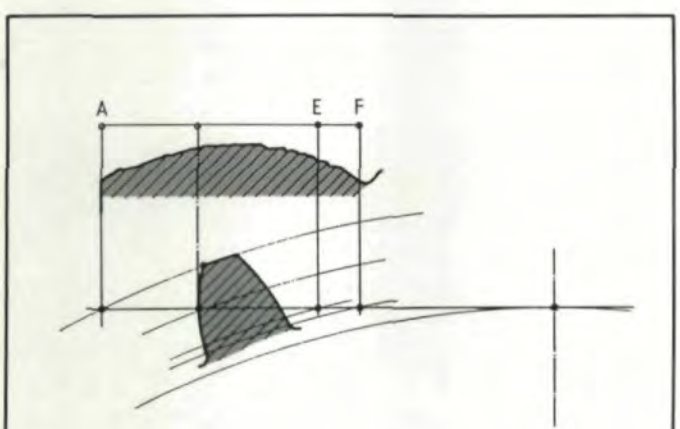

Fig. 9—Relation between involute tooth profile and profile diagram

proportional to the length, L_{AF}, of the base tangent between the two end points of the involute profile or the length, L_{AE}, corresponding with the active profile. (Fig. 9)

After checking, the actual profile is compared with the design profile (involute or modified involute) and the profile deviations are determined according to gear standards.

For recording the profile quality of very large gears, development goes mainly in the direction of applying measuring systems which are either transportable or fitted on to the gear production machine.

In cases where profile checking on large gears is not possible, the profile slope accuracy may be controlled by the auxiliary method of measuring the absolute value of the base pitch, for example, by using the hand instrument shown in Fig. 3. For this purpose, the instrument needs to be calibrated with an appropriate gauge. However, as measured values of base pitches are influenced by both pitch deviations and flank form deviations, this substitute procedure is only of reasonable use if pitch and flank form accuracy is very high.

Preferably, the actual absolute base pitch is determined as a mean value of several flanks. It must be assured that the measuring contact points do not lie in zones with profile or helix modifications.

With respect to the high costs of remachining a large gear, a "wrong" profile slope or pressure angle with does not correspond with the theoretical or the design value, in many cases is not corrected, but the mating pinion is machined to the same "wrong" value: If gear and mating gear have the

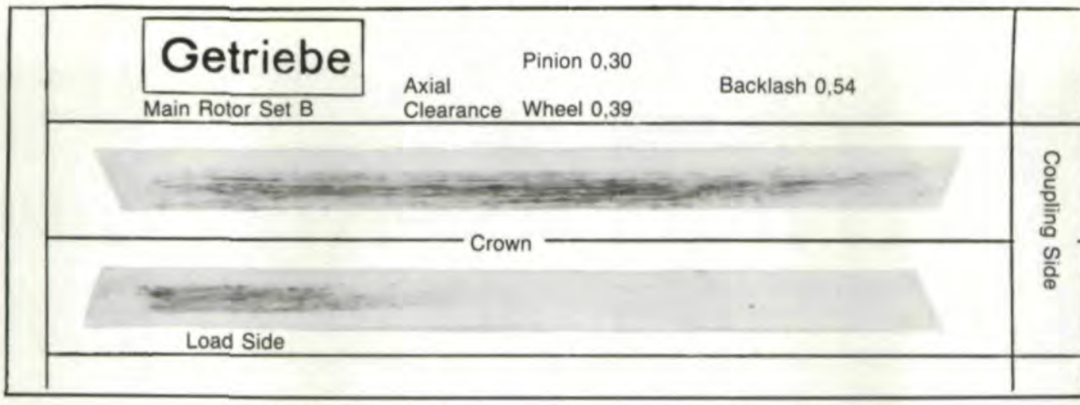

Fig. 10—Example of a recorded contact pattern configuration

same plus or minus profile slope deviation, the deviation is mutually compensated for and flawless meshing is attained in spite of the difference between theoretical and actual value.

Checking of Helix

Helix accuracy is usually depicted by the helix diagram, the length of which is equal or proportional to the usable face width. It shows the helix deviations relative to a straight line, the latter representing the unmodified pure helix.

In the past, for lack of checking equipment, the helix quality of very large gears and the mutual matching accuracy between gear and pinion have exclusively been inspected either by inserting a feeler guage between the flank and its mate flank or by examining the gear tooth contact pattern. By the latter means, a thin, even layer of blue or red dye is applied to a few consecutive teeth of the gear. Then, with the pinion shaft braked, the gear is rotated back and forth, so that the colored teeth pass through mesh several times. Fig. 10 shows an example of a recorded pattern configuration obtained by placing transparent adhesive tape to the pinion flank. This no-load tooth contact test (normally made on the working flanks, on a meshing rig or in the gear box) is performed on the non-working flanks if the working flanks are provided with relatively pronounced helix modifications, rendering them unsuitable for this test.

Helix misalignment, sometimes only ascertained when the gears are assembled in the gear box, is generally corrected by remachining of one of the mating gears or, especially in the case of single helical gears, by appropriate setting of specially designed adjustable bearings.

Newly developed more accurate checking equipment contributes to more economical production of large gears in that the helix contour can be measured to a very high reliability, either directly on the production machine or on a gear measuring center. Together with the improved accuracy in machining the bores in the gear boxes, expensive adjustable bearings or even more costly remachining of gear elements can be avoided.

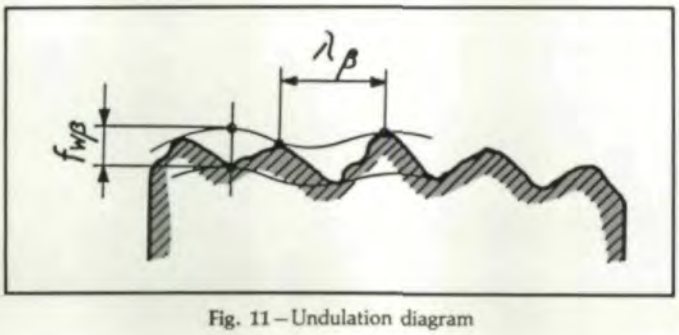

Fig. 11—Undulation diagram

Checking of Undulation

The (helix) undulation is defined as the total wave height ($f_{w\beta}$) of waves of like height and like wave length ($_\beta$) along the helix of helical gears. (Fig. 11)

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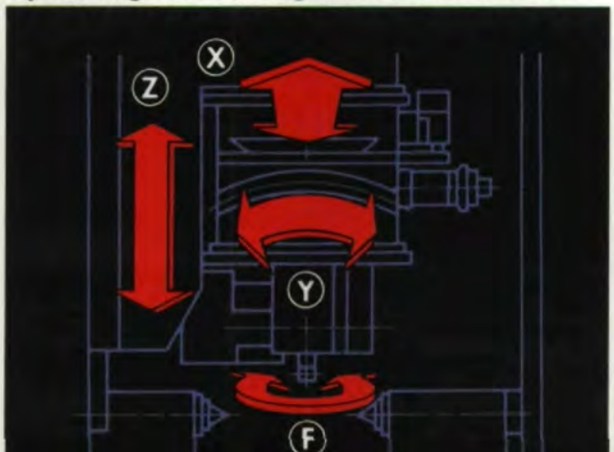

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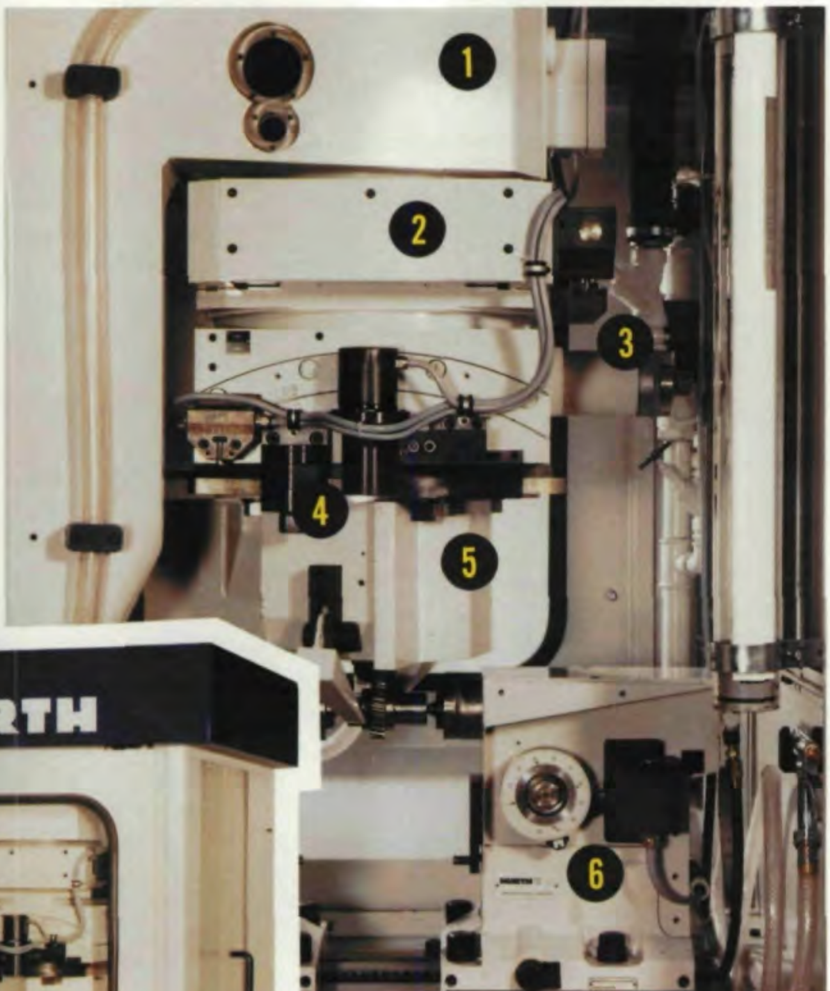

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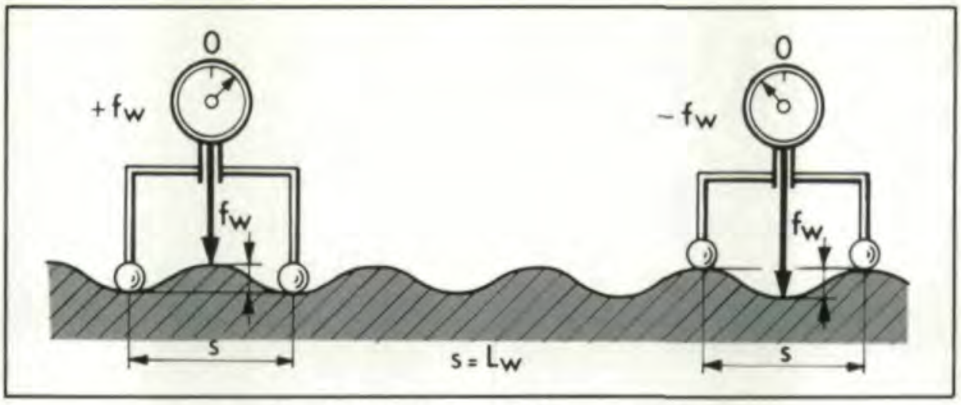

Fig. 12 – Principle of undulation measurement

Due to the characteristic of equally distant flank deviations causing accelerations of constant frequency, even slight undulations can impair the performance quality (vibration, noise, surface load endurance) of a gear train considerably. Therefore, it is often necessary to restrict undulation amplitudes to relatively stringent tolerances. Generally, by projection on the circumference, the wave length allows determination of the number (n_M) of periodic machine disturbances occuring around the whole gear circumference. See below.

$$n_M = \frac{d \cdot \pi}{\lambda\beta \cdot \tan\beta} \text{ with } \lambda\beta \text{ in direction of axis}$$

$$n_M = \frac{d \cdot \pi}{\lambda\beta \cdot \sin\beta} \text{ with } \lambda\beta \text{ in direction of helix}$$

where d = pitch diameter, and β = helix angle.

As to the sources of helix undulations, those of particular interest are attributed to the worm gear mechanism of work tables of gear generating machines: The ridges and troughs of undulations caused by tooth meshing defects of the worm gear drive or by its location bearings run parallel or nearly parallel to the straight generators of the machined helical tooth flanks. If the worm gear drive uses a single thread worm, which is mostly the case, the projection of the undulation on the circumference of the gear represents an integral part of the whole circumference. Hence, the resulting meshing defect impairs the gear performance by an unbroken cyclic vibration. The number of undulations around the machined gear is equal to the number of teeth of the table worm wheel.

The relevant wave length appearing in the helix diagram or in the undulation diagram, related to direction of gear axis, is given by

$$\lambda\beta = \frac{d \cdot \pi}{\tan\beta}$$

Helix undulation measurements according to the principle of Fig. 12 show double the amount of the actual undulation error $f_{w\beta}$. Distance, s, between the sliding pads is to be set either to the supposed wavelength, β, or to an uneven multiple of it; with s equal to an even multiple of β, the recorded value would theoretically be zero.

Machines and Instruments for Checking Large Gears

According to the demands of industry, development of gear testing equipment has to assure utmost accuracy, ease of operation, and in the interest of economics, short measuring times. Because documented inspection has become more and more essential, automatic recording and analysis of measuring is also a requirement.

The instruments and systems described in the following are examples of developments embodying these aims.

Measuring Machines for Gears up to Two Meters

Machines have been designed for gears up to 2000 millimeters in diameter and up to a weight of 1200 kilograms. They are capable of checking profile, helix and, together with additional devices, pitch, run-out, undulation and surface roughness of tooth flanks.

Before starting the measurement, the stylus is automatically set to the flank to be checked. By means of the optional recording and analyzing system which incorporates a desk computer, the test results can be numerically recorded, stored, analyzed and plotted. The software system allows a wide selection of program options suited for individual requirements.

The typical measuring accuracy achieved on the checker can be quantified by the following formulas:

$$\text{Profile: } 0.35 + \frac{\psi}{28} + \frac{d}{2800} \ (\mu m)$$

$$\text{Helix: } 0.35 + \frac{\sqrt{b}}{15 \cos \beta} \ (\mu m)$$

whereby ψ = roll angle in degrees
d = pitch diameter in mm
b = face width in mm
β = helix angle

For a sample gear of 6.8mm module, 1800mm pitch diameter, 325mm face width, 18° helix angle and 3.3° rolling angle (root to tip), the measuring uncertainty for profile and for helix amounts to 1.1 and 1.6 μm, respectively, for typical absolute accuracy (U_{95}); 1.6 and 2.3 μm, respectively, for guaranteed absolute accuracy; 0.4 and 0.7 μm, respectively, for guaranteed repeatability.