MAAG
ZURICH

METROLOGICAL INSPECTION OF GEARS

by

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Gear Inspection Technology

Evaluation criteria, inspection methods, measuring instruments and their accuracy.

1 Different Quality Criteria

Together with an appropriate gear design, suitable material, flawless heat treatment, rigid housing, adequate bearings and good lubrication, the geometric accuracy of the toothing is a first essential for the good performance of a gear.

As figure 1 illustrates, there are many different kinds of gear deviations which all together represent the accuracy grade of a gear.

In the interest of an economic production, not all the defined deviations or characteristics such as pitch, cumulative pitch, profile, helix, undulation, surface finish, radial run out, radial and tangential composite deviations are to be measured on each gear because in a specific case, not all of these characteristics are important. Alternatively certain kinds of deviation are already known from experience on the machine tool used, or one measurement may be substituted for another, e.g. the tangential composite test for the cumulative pitch inspection or the radial composite test for the runout inspection.

The inspection methods to be employed depend on the functional application and the quality grade of the gear, in some cases also on the manufacturing method and on the gear size (availability of relevant inspection equipment). The following observations describe the most important methods in gear quality control.

2 Accuracy of the Gear Body

An important requirement for producing an exact gear is a sufficiently accurately made gear body. The axis of the gear must be defined by the reference faces. As well as the important dimensions, the radial and axial run-out of the bearings and sometimes, according to the demands, of the tip cylinder are to be checked.

3 Inspection of Gear Teeth

3.1 Inspection of Pitch Accuracy

Pitch inspection determines the actual distance between, or the relative positions of, corresponding flanks around the circumference of the gear. Figure 3 shows the single pitch deviation f_{pt}, the transverse base pitch deviation f_{pbt}, and the cumulative pitch deviation F_{pk} with k equal to 3. Figure 4 illustrates the conventional representation of the deviations in diagram form, for a sample gear with 18 teeth.

3.1.1 Measurement of single pitch deviation f_{pt}

The single pitch accuracy is chiefly checked either by the chordal or by the angular method.

Chordal measurement

With this method the length of chord, between the points of feeler contacts, is measured. Apart from hand instruments which are set on the outside diameter of the gear, automatic apparatus are used which move two feelers radially to the gear to always the same depth (Fig. 5). The gear rotates slowly around its axis, and the feelers are moved in and out in an appropriate rhythm.

The difference between each measured value and the mean of all such measurements around the circumference is equal to the single pitch deviation f_{pt} (Fig. 4a).

Angular measurement

The angular measurement employs the theoretic angular pitch $T = 360°/z$ as the measuring basis. Measuring instruments usually apply optical or electronic dividing equipment whereby a pick-up senses the actual position of the flank (Fig. 6). Every value displayed by the read-out represents the position deviation of the relevant flank, with respect to the selected reference of zero flank. With this method, the single pitch deviation f_{pt} results as the algebraic difference between the readings for two consecutive flanks.

3.1.2 Measurement of Base Pitch p_b

Differentiation is made between the base pitch in the normal section (p_{bn}) and in the transverse section (p_{bt}, Fig. 7). The purpose of base pitch measurement, apart from the inspection of pitch uniformity as a possible substitute for the single pitch measurements as per section 3.1.1, can also be to measure the absolute value of the mean base pitch, as a makeshift determination of the base circle, the mean profile slope or the mean pressure angle deviation. In order to inspect pitch uniformity, the difference between the individual readings and their arithmetic average around the circumference is determined.

Measurement is mostly performed with hand instruments. If the absolute value is to be determined, the instrument is calibrated with an appropriate gauge (Fig. 8).

3.1.3 Determination of Cumulative Pitch Deviation F_{pk}

The cumulative pitch deviation is the sum of the single pitch deviations of a specified number (k) of consecutive pitches.

When applying chordal measurement, cumulative pitch deviations are obtained by algebraic summation of the transverse pitch deviations.

When applying angular measurement, every gauge reading gives a plot point of the cumulative pitch deviation graph (Fig. 4b, F_{pk} curve).

3.1.4 Determination of the Total Cumulative Pitch Deviation F_p

The total cumulative pitch deviation is equal to the maximum cumulative pitch deviation occurring around the gear circumference ($F_p = F_k$max.) and may be determined from the cumulative pitch deviation curve: It is defined as the distance between the highest and the lowest point of the curve (Fig. 4b).

3.2 Inspection of the Profile

On most testing apparatus, the tooth profile is scanned with a feeler. The workpiece and/or the feeler are moved relative to each other such that the feeler follows the profile contour.
Generally, the profile contour of a gear flank is illustrated by a diagram where the nominal involute is represented by a straight line. The profile deviation as well as any design profile modification appear in magnified amounts as a deviation from this straight line.

Apart from the total profile deviation F_α, also the profile from deviation f_f and the profile slope deviation f_H can be determined by applying the so-called mean profile as a reference basis (Fig. 9). Furthermore, evaluations, with respect to a specified tolerance field, a special design profile, or profile crowning, are possible.

3.3 Inspection of the Helix

Helix inspection apparatus are mostly designed to record the unmodified helix as a straight line. Thus, planned modifications, as for instance helix crowning or end reliefs, are recorded in magnified amounts as deviations from this straight line.

The evaluation of the total helix deviation F, the helix form f_f, and the helix slope deviation f_H is similar to the inspection of the profile (Fig. 10).

When needed, evaluation with respect to helix undulation f_W (in most cases with special testing equipment), or to special design helices and helix crowning can be made.

4 Apparatus and Machines for Gear Inspection

4.1 Trend of Development

Accurate gears can hardly be manufactured without careful inspection of the toothing. Taking also into account the economic aspect, development of gear measuring equipment is directed towards five main objectives:

1) Accuracy of measurement
2) Short inspection time
3) Automatic determination of inspection and analysis results
4) Inspection of all important quality items on one set-up
5) Measuring on the machine tool, particularly in the case of large workpieces

Some examples of modern gear inspection equipment, as described in the following sections, give an overview on the present stand of today's inspection technology.

4.2 Profile and Helix Inspection Machine PH-40 with Interchangeable Base Discs

The inspection machine shown in Fig. 11 was made mainly for production control of small to medium size gears of up to 400 mm diameter. It generates the relative (reference) motion by mechanical means, i.e., by rolling the interchangeable base disc on the generating rule.

To take into account the different customer requirements for metric or inch or roll degree scales, digital display, hand operation, on the fully automatic concept with automatic loading (PH-40, Fig. 12), this type was developed with 24 standard options.

The measuring accuracy is about 1 micrometer.

For a typical automobile gear, the inspection time for 4 profile and helix diagrams on both flanks and 4 teeth around the circumference (16 diagrams) amounts to approx. 4 minutes.

Fig. 13 shows a sample of a plotted sheet.

4.3 CNC Gear Measuring Centers SP-42 and SP-65

These machines are for maximum diameter of 420 or 650 mm respectively (example shown in Fig. 14) and generate the reference curves of measurements, such as involute, helix, pitch, etc., by optical-electronic means and an integrated computer control. The system concept permits a fully automatic operating procedure and automatic loading.

Data input is either via the keybord of the desk computer, and dialogue with the display screen, or via a diskette and re-call with a code number.

Measuring accuracy and inspection times are about the same as on the machine PH-40.

The output of the inspection and analysis results is displayed on-line or down loaded from an intermediate storage to a modern plotting system. A statistic software program allows the results to be stored according to selected criteria, and to be recalled for statistical evaluation.

4.4 Gear Inspection Machines SP-130, SP-160, and SP-200 with Adjustable Base Circle

The machines of the series according to Fig. 15 are capable of inspecting profile, helix, and, with additional equipment, also pitch, surface roughness and run-out of gears of up to 2 m diameter and a weight of 12 tons.

Reference curve motions are achieved by mechanical means with a non-slip generating drive and a variable lever transmission.

The diagrams of Fig. 16 indicates the high accuracy of the machine. All 3 diagrams have been taken at the same profile trace, but with the kinematic reference chain of the machine shifted into 3 different relative positions, so that any error of the machines is shown up as a deviation in the diagram. The deviation observed here was less than half a micrometer.

4.5 CNC Gear Measuring Centers MC-200 and MC-400 Integrated on Manufacturing Machine

With the measuring system shown in Fig. 17, the following quality characteristics can be checked:

- Profile, in an x/y coordinate plane, the workpiece remaining stationary.
- Helix, with synchronised motions of the vertical feeler path and of workpiece rotation
- Single and cumulative pitch, with the workpiece slowly rotating
- Helix undulation, with same motions as used in helix inspection, but with a special undulation pick-up
- Surface roughness, with the use of an appropriate attachment.

The operating range is adapted to the relevant manufacturing machine, i.e., to 2 m or 4 m maximum diameter, respectively.

4.6 CNC Gear Measuring Centers MCR-250 and MCR-500

By the addition of a circular table for the workpiece, the systems MC described above can be expanded to produce an independent measuring center (Fig. 18).

Maximum values of operating ranges are:

	diam.	weight	face width	module
MCR-250	3000 mm	18 t	1100 mm	40 mm
MCR-500	2500 mm	50 t		

4.7 Mobile Inspection Equpiment

In addition to the stationary inspection machines and measuring centers, some mobile equipment is available for the use on stationary gears, manufacturing equipment, or on gears that have already been installed.

The profile tester ES-430 (Fig. 19) which works on the base of a x/y coordinate concept can be applied to horizontal or vertical axis gears. It also permits the re-inspection of gears mounted in assembled gear units.

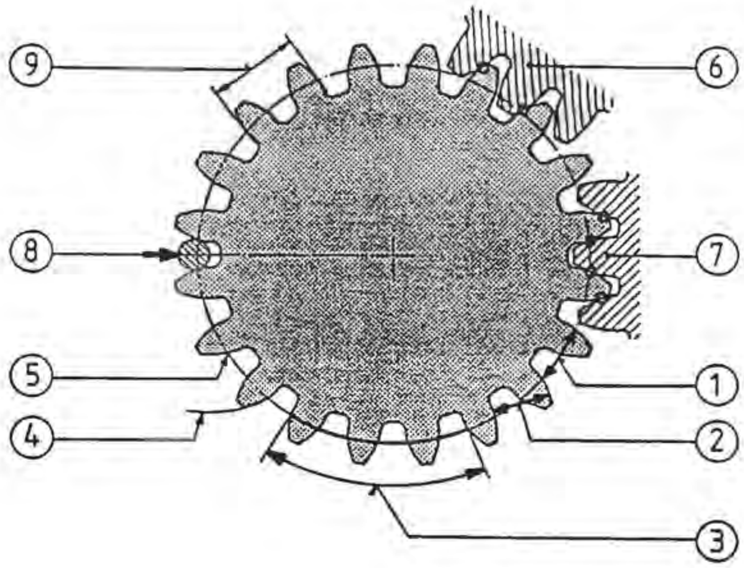
The tester works within an absolute accuracy of approx. 1 micrometer.

The pitch inspection instrument ES-401, shown in Fig. 20, is applied very universally to the inspection of horizontal or vertical axis gears. It works on the principle of chordal pitch measurement and its single pitch measuring accuracy is about 0,2 micrometer. In order to use this instrument the gear under inspection is slowly rotated during measurement.

5 Allowable Gear Deviations, Comparison Between ISO, DIN, AGMA and MAAG SI

The diagrams of Fig. 21 and 22 show, as examples, the amounts of allowable gear deviations for single pitch and profile, according to ISO 1328 (1975), DIN 3961/62 (1978), AGMA 390.03 (1971) and MAAG SI (1963), for the range of module 6 to 10.

Standard Gear Deviations



1	Single pitch deviation	f_{pt}
2	Base pitch deviation	f_{pb}
3	Cumulative pitch deviation	F_{pk}
	Total cumulative pitch deviation	F_p
4	Total profile deviation	F_α
5	Total helix deviation	F_β
	Helix undulation	$f_{w\beta}$
6	Tooth-to-tooth tangential composite deviation	f_i'
	Total tangential composite deviation	F_i'
7	Tooth-to-tooth radial composite deviation	f_i''
	Total radial composite deviation	F_i''
8	Run-out	F_r
9	Base tangent length	W_k

1 ÷ 6 Related to single flank contact (on right or on left flanks)

7 ÷ 9 Related to double flank contact (on right and left flanks)

Fig. 1 Standardized types of gear deviations

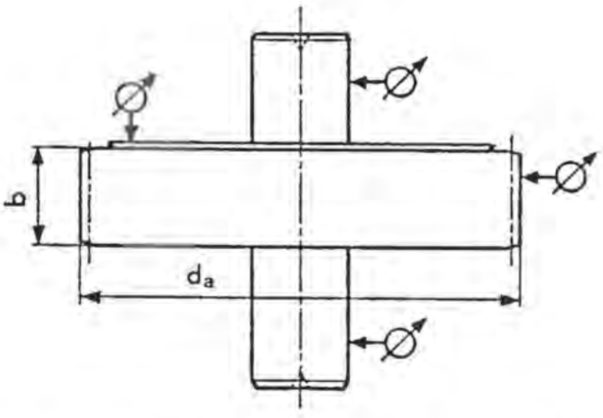


Fig. 2 Inspection of the gear body

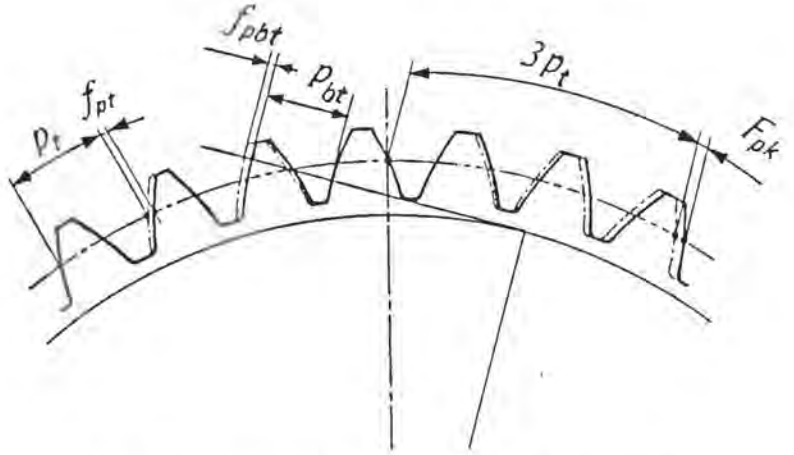


Fig. 3 Standardised pitch deviations

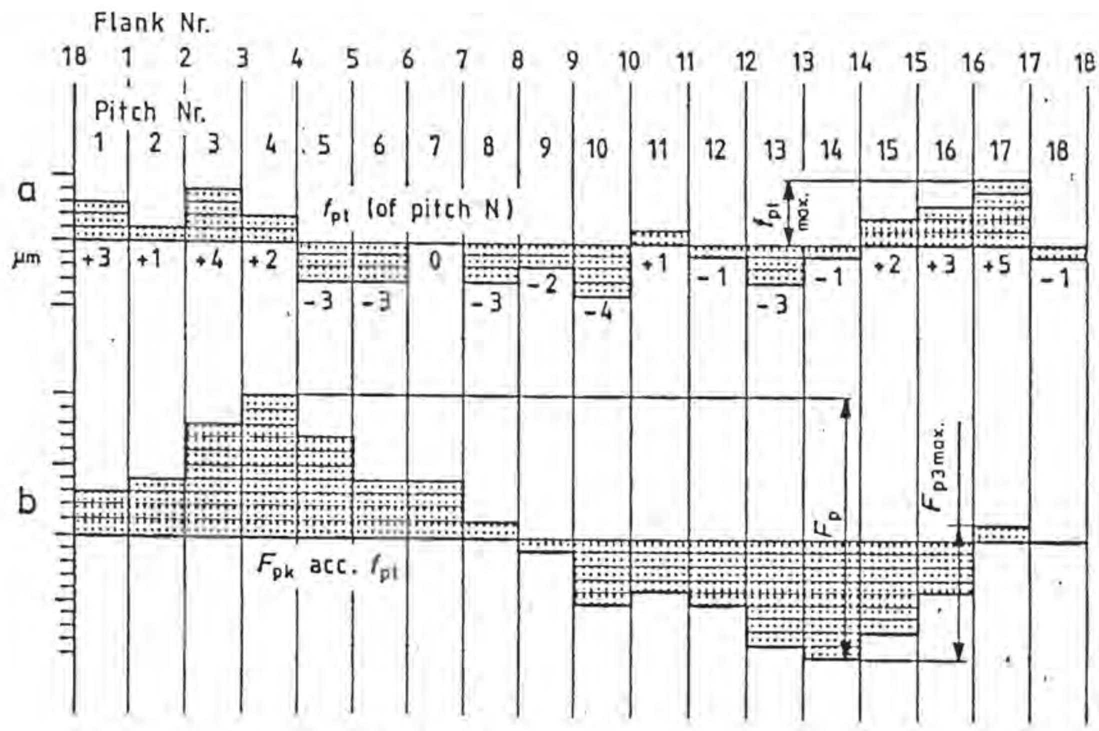


Fig. 4 Pitch deviations in diagram form

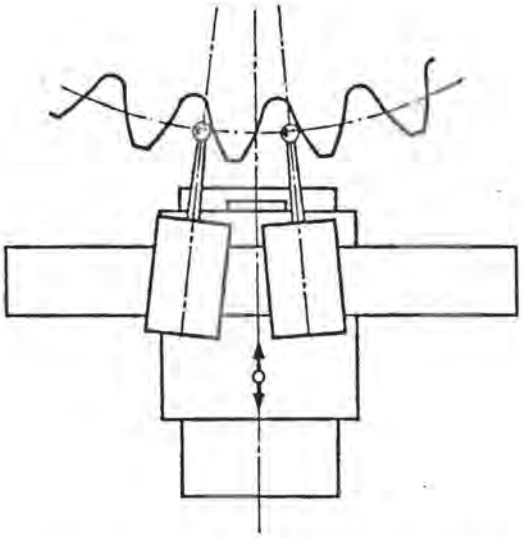


Fig. 5 Principle of chordal measurement

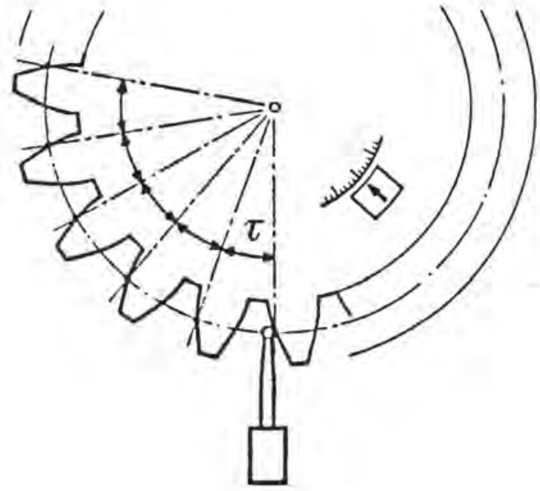


Fig. 6 Principle of angular measurement

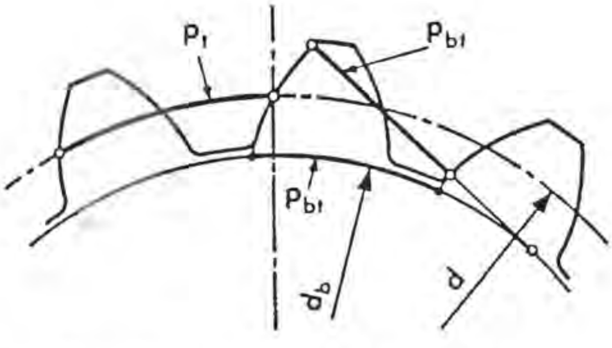


Fig. 7 Transverse base pitch p_{bt}

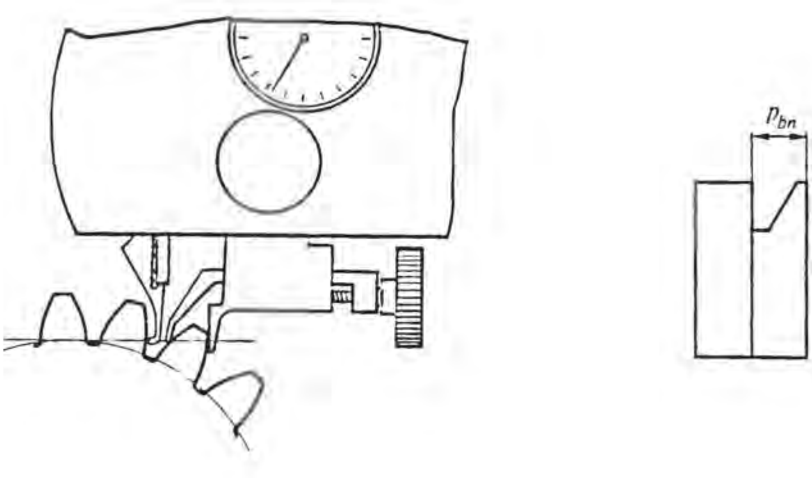
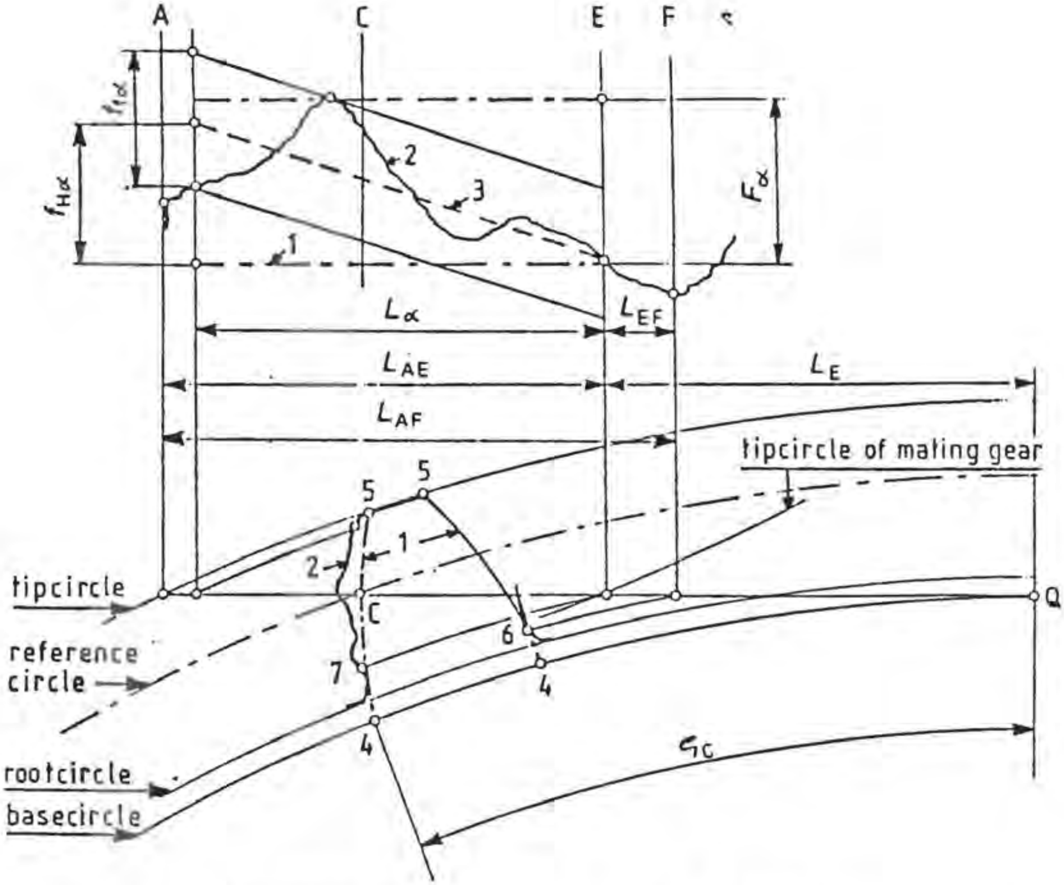


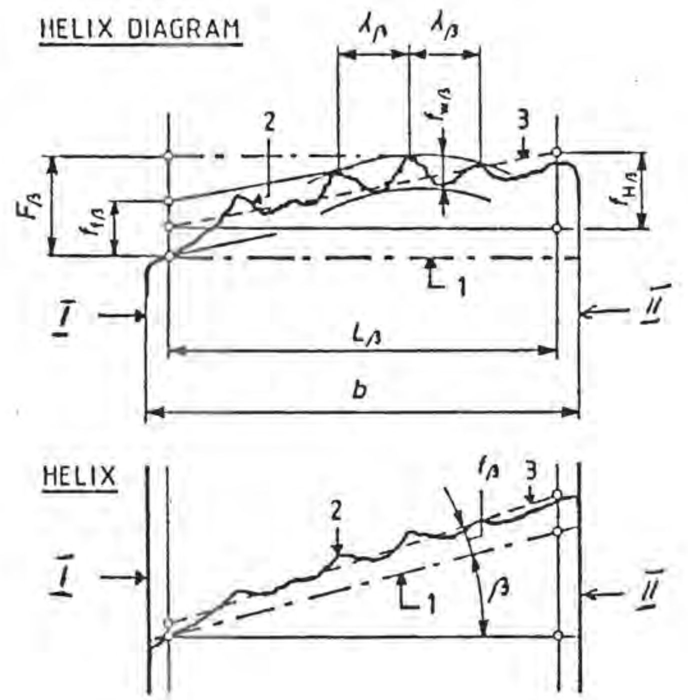
Fig. 8 Hand instrument for measuring base pitch and calibration gauge



TOOTH PROFILE	
1	:Design profile
2	:Actual profile
3	:Mean profile
4	:Origin of involute
5	:Tip point
5-6	:Usable flank
5-7	:Active flank
C-Q	:Path of roll of point C
φ_C	:Angle of roll of point C

PROFILE DIAGRAM	
A	:Tooth tip or start of champfer
C	:Pitch point
E	:Start of active flank
F	:Start of usable flank
L_{AF}	:Length of diagram of usable flank
L_{AE}	:Length of diagram of active flank
L_α	:Evaluation range
L_{EF}	:Unused part of usable flank
F_α	:Total profile deviation
$f_{f\alpha}$	:Profile form deviation
$f_{H\alpha}$	:Profile slope deviation

Fig. 9 Profile diagram and profile deviations



HELIX

1 : Design helix

2 : Actual helix

3 : Mean helix

b : Facewidth ⊕

L_β : Helix evaluation range

f_β : Helix deviation

HELIX DIAGRAM

F_β : Total helix deviation

$f_{f\beta}$: Helix form deviation

$f_{H\beta}$: Helix slope deviation

λ_β : Wavelength of undulation

$f_{w\beta}$: Undulation

Fig. 10 Helix diagram and helix deviations

Fig. 11 Profile and helix inspection machine PH-40

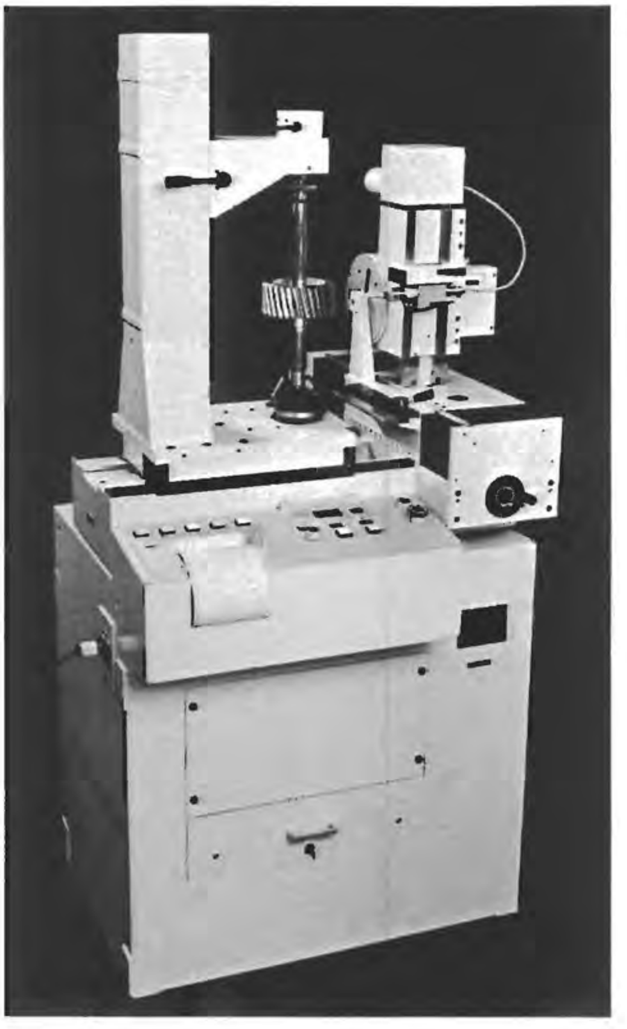


Fig. 12 Automatic profile and helix inspection machine PH-40A

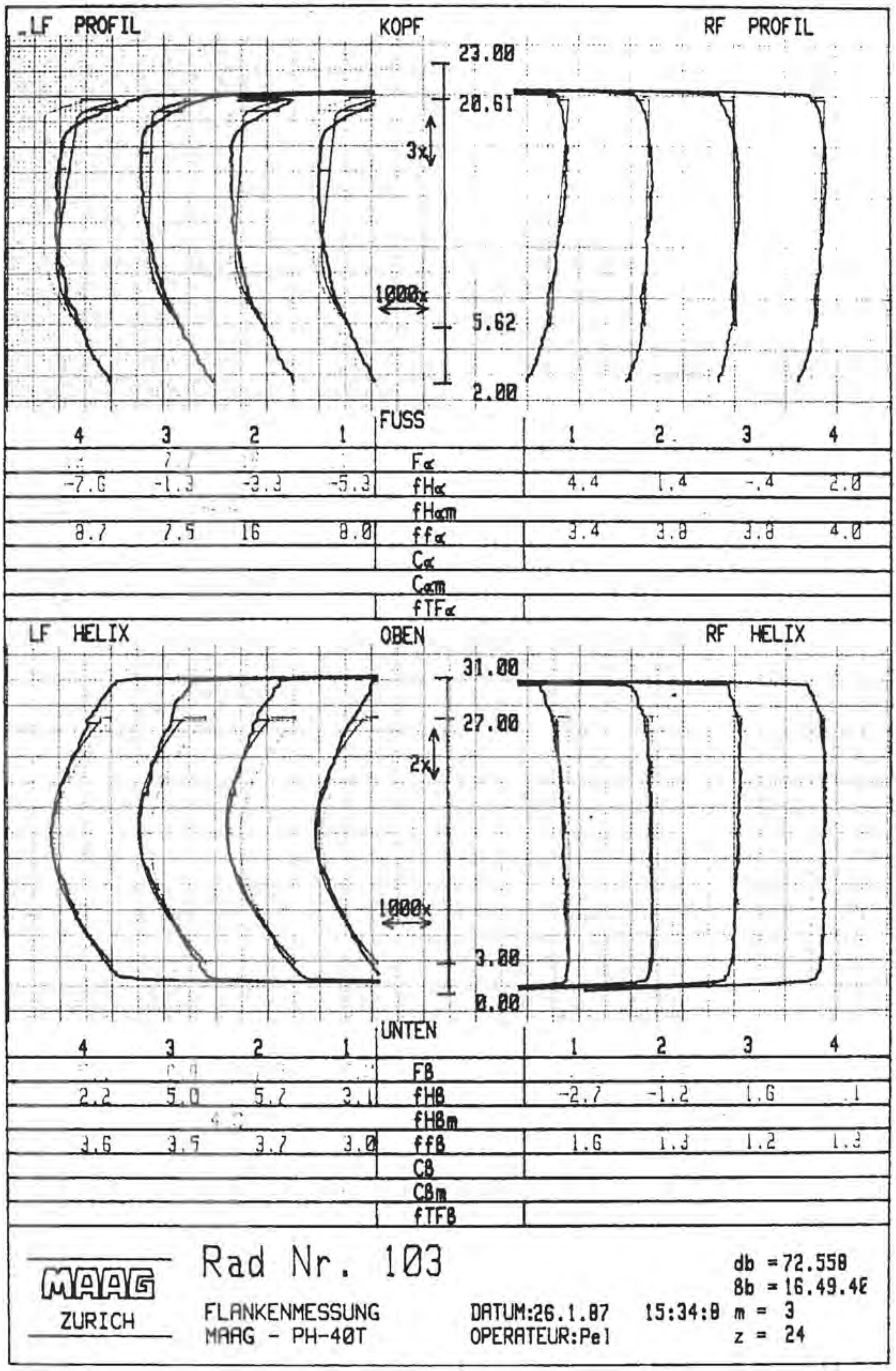


Fig. 13 Plotted chart with profile and helix diagrams and relevant numerical values

Fig. 14 Automatic CNC gear measuring center SP-42

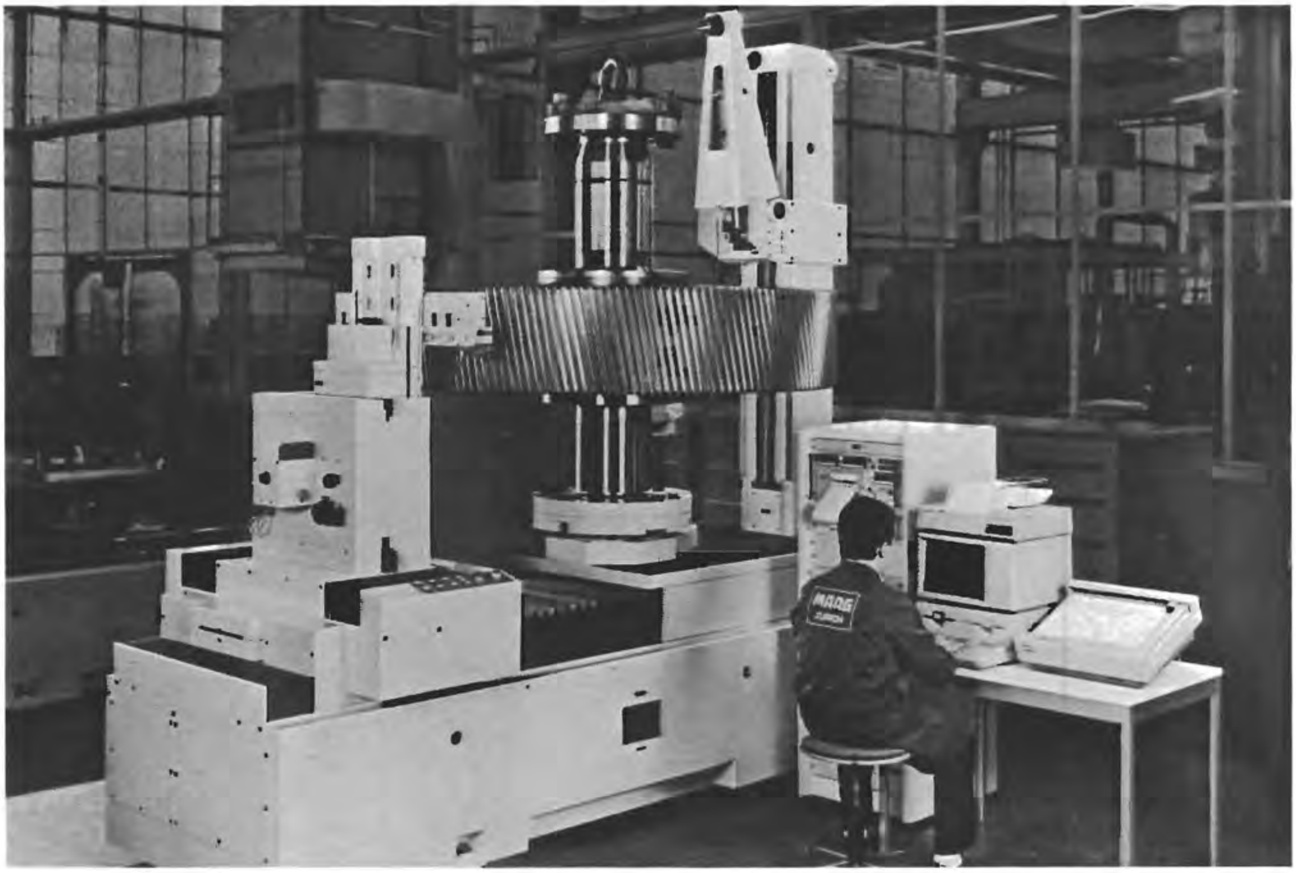


Fig. 15 Gear inspection machine SP-160

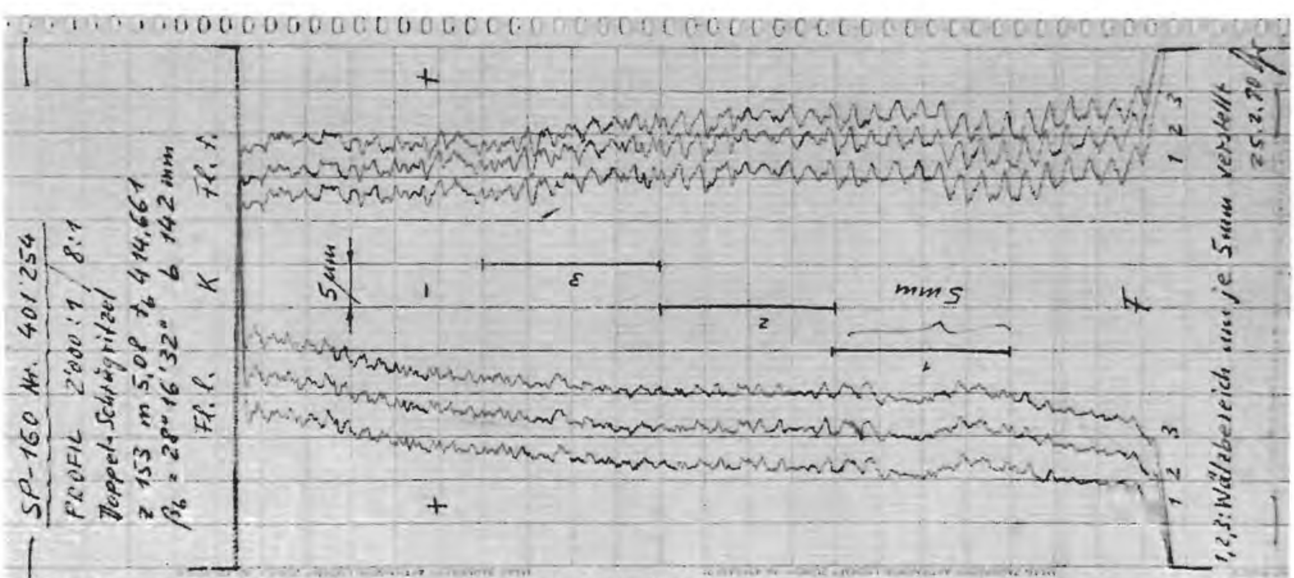


Fig. 16 Profile diagrams, repeated 3 times with different positions of the kinematic chain

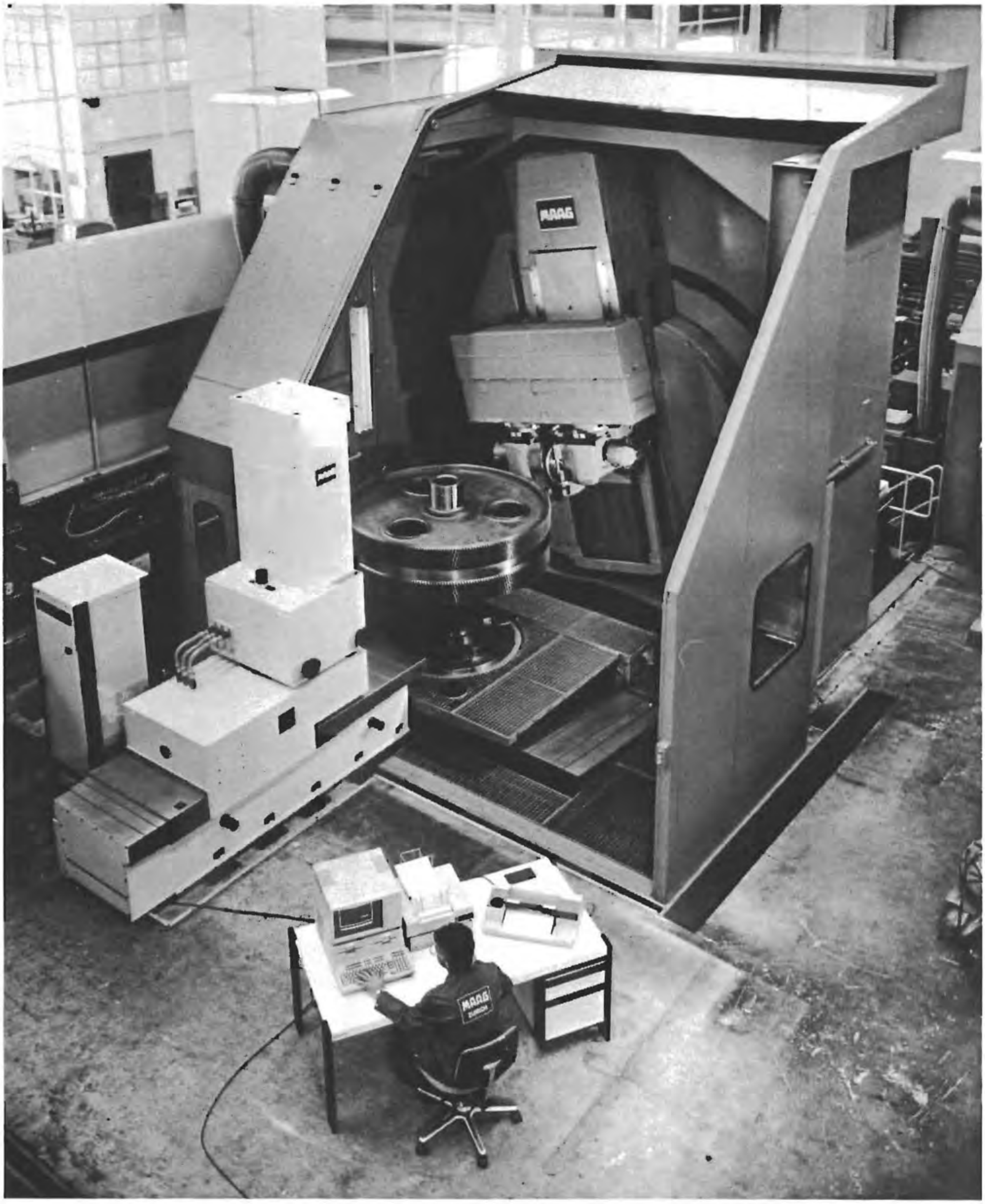


Fig. 17 CNC gear measuring center MC-200 on a SE-200 grinding machine

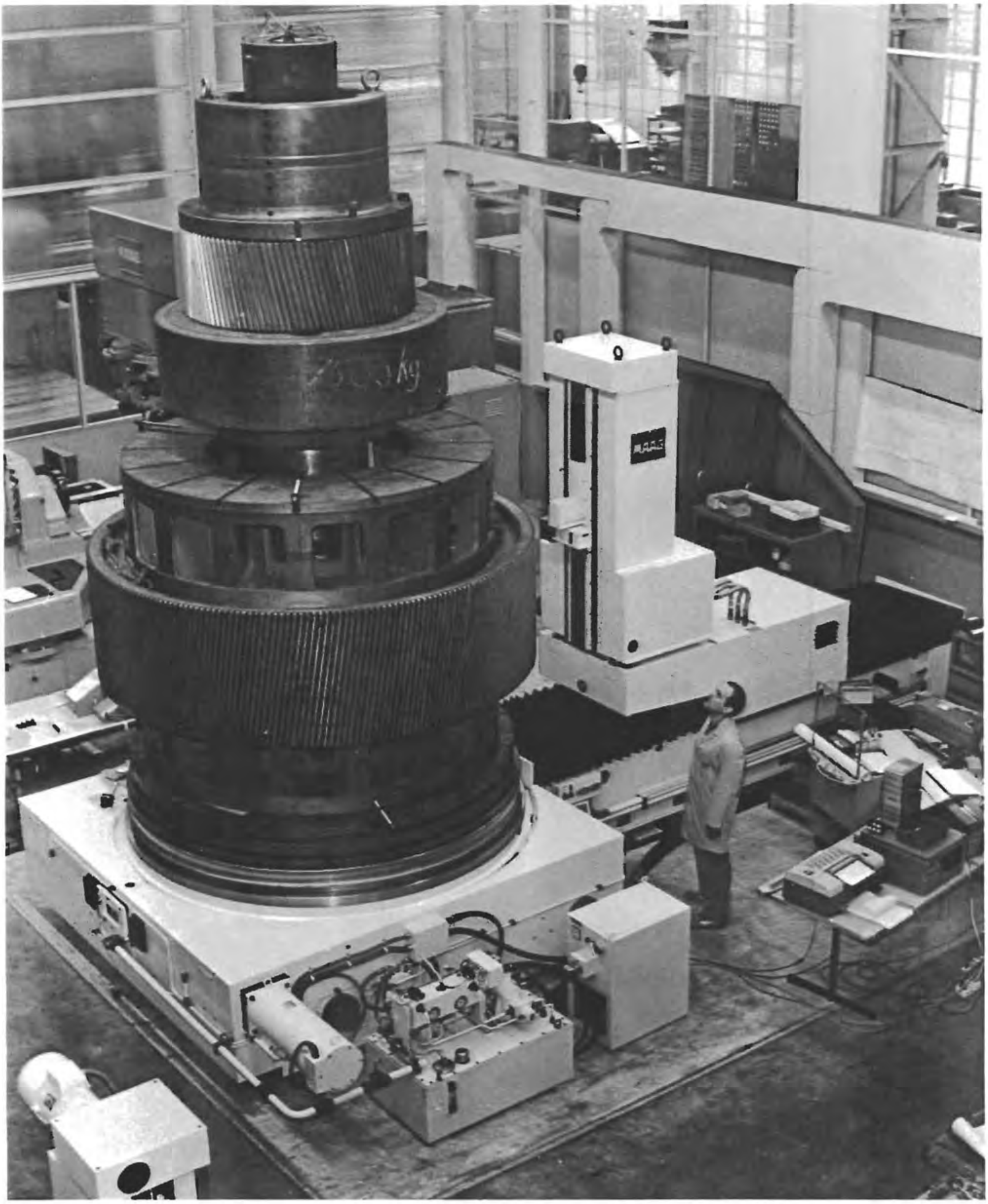


Fig. 18 CNC measuring center MCR-500 for large gears. Weight test

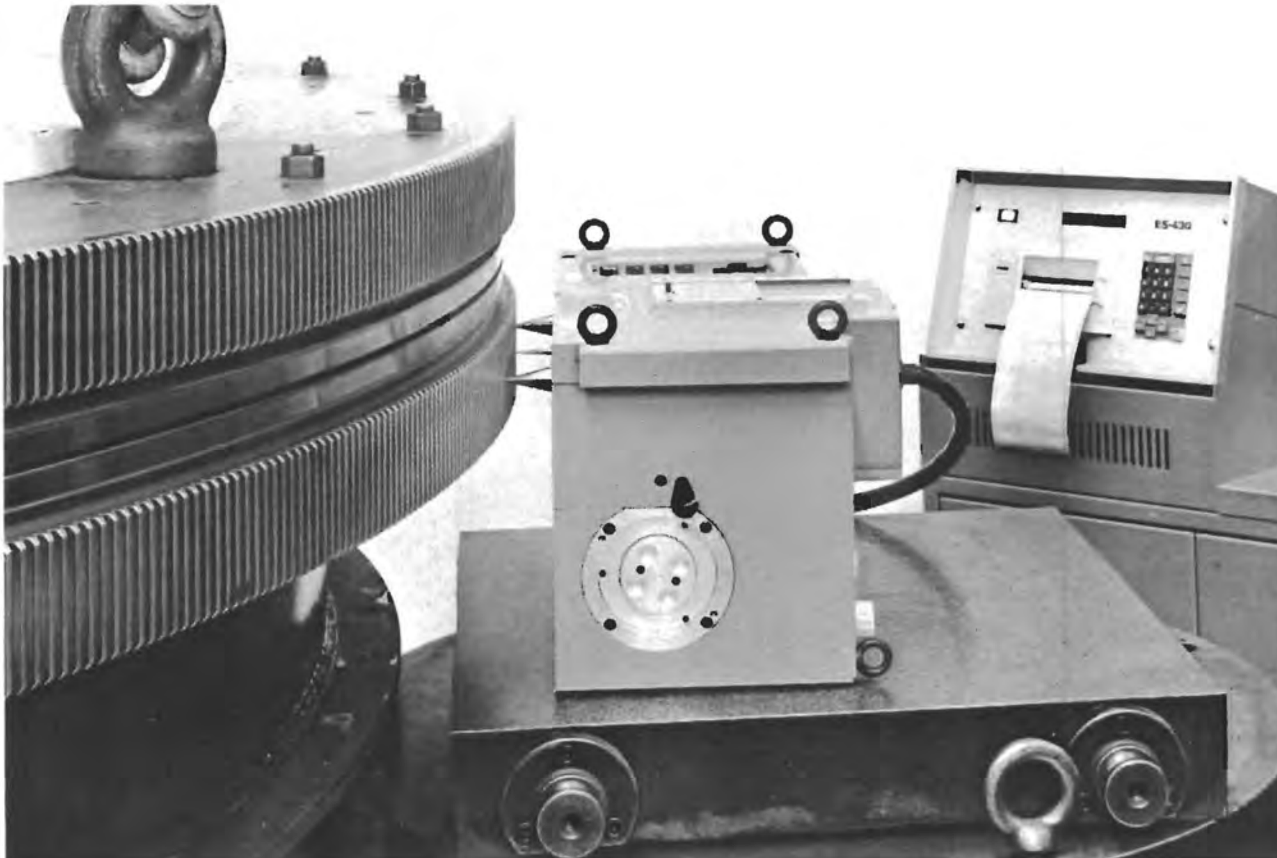


Fig. 19 Mobile profile tester ES-430

Fig. 20 Mobile pitch inspection instrument ES-401

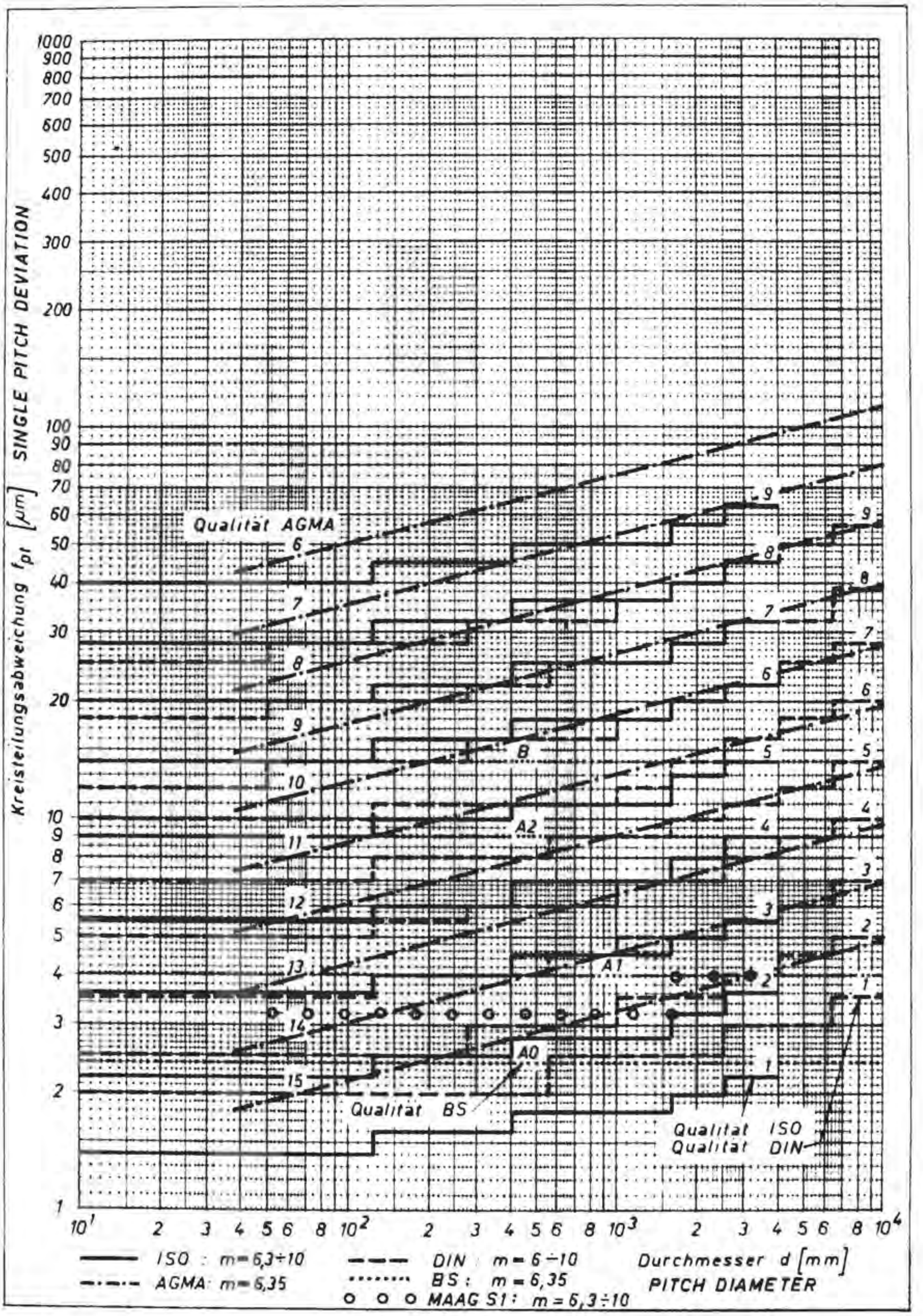


Fig. 21 Single pitch deviations, Comparison between quality systems ISO, DIN, AGMA, BS and MAAG S1

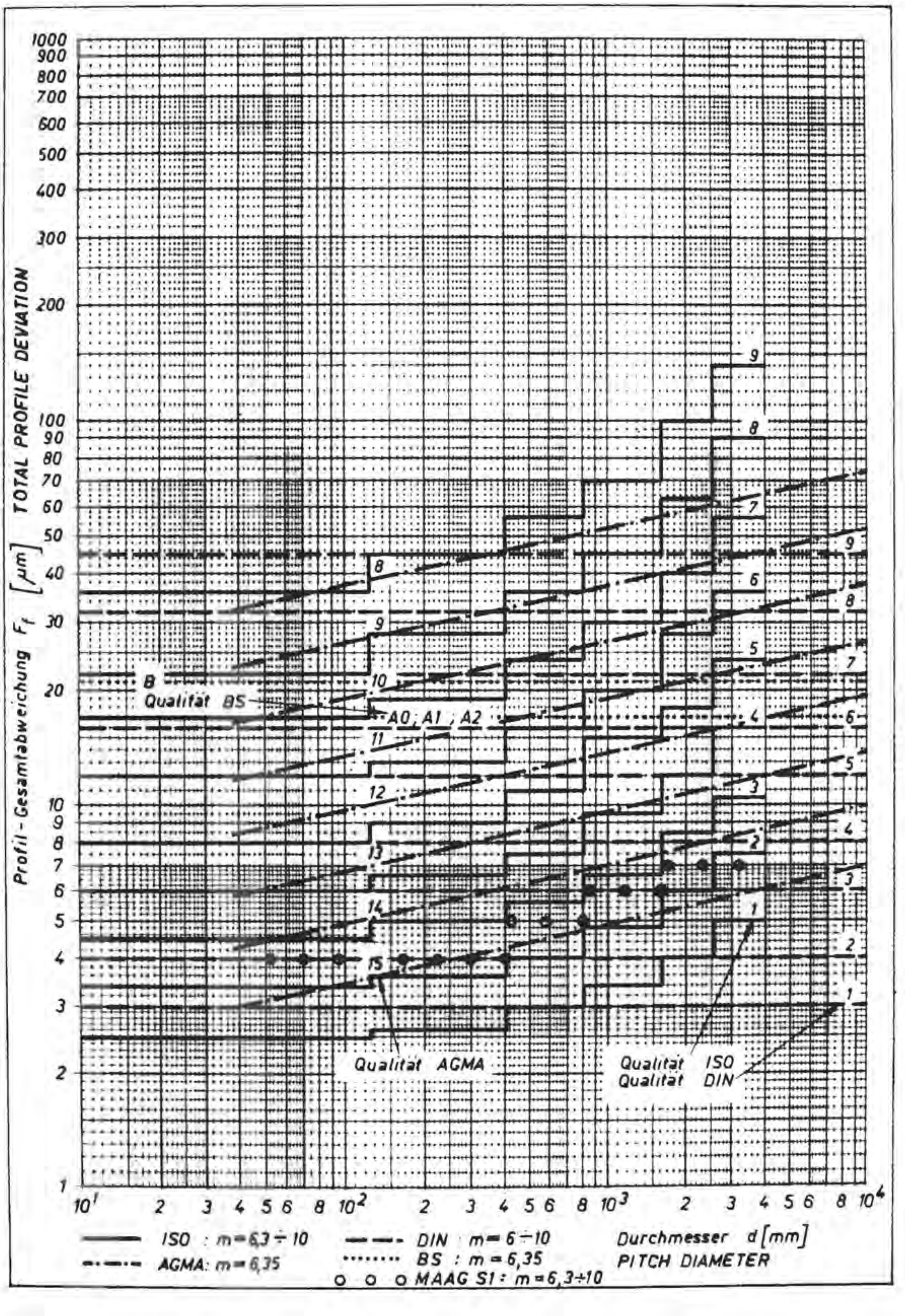


Fig. 22 Total profile deviations. Comparison between quality systems ISO, DIN, AGMA, BS and MAAG S1