Worm Gear Measurement

Cedric Barber

Several articles have appeared in this publication in recent years dealing with the principles and ways in which the inspection of gears can be carried out, but these have dealt chiefly with spur, helical and bevel gearing, whereas worm gearing, while sharing certain common features, also requires an emphasis in certain areas that causes it to stand apart. For example, while worm gears transmit motion between nonparallel shafts, as do bevel and hypoid gears, they usually incorporate much higher ratios and are used in applications for which bevels would not be considered, including drives for rotary and indexing tables in machine tools, where close tolerance of positioning and backlash elimination are critical, and in situations where accuracy of pitch and profile are necessary for uniform transmission at speed, such as elevators, turbine governor drives and speed increasers, where worm gears can operate at up to 24,000 rpm.

Most quality worm gear sets consist of a parallel worm having the thread flanks in the form of an involute helicoid developed from a base circle. The worm wheel is generated by a cutter, the shape and radius of which approximate the form and size of the mating worm with detail differences that may be unique to the manufacturer. This article deals specifically with this type of worm gear, although most of the following features and procedures are applicable to all-enveloping and concave worm gearing as well.

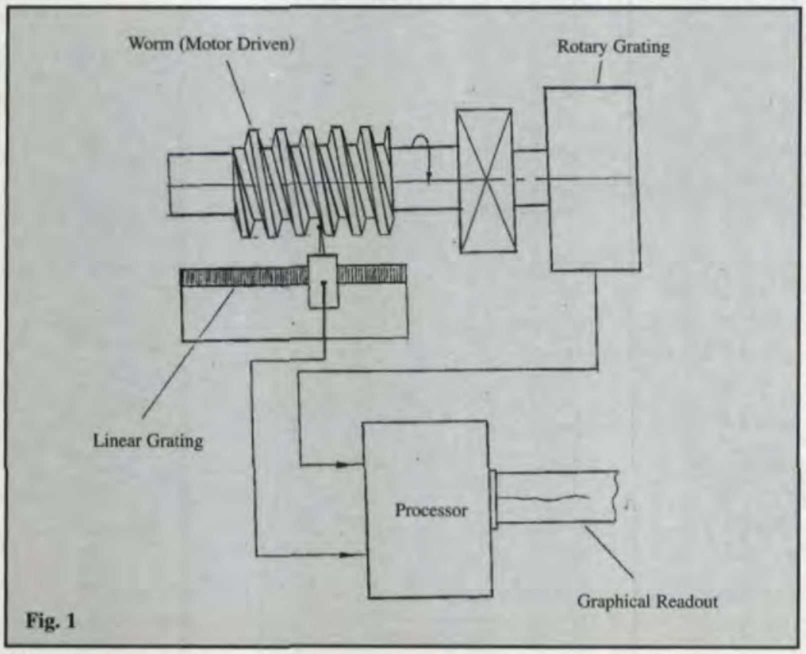

Fig. 1

Definition of Terms

The Worm Shaft. *Axial pitch deviation* is the difference between the design pitch and the actual measured pitch of a designated number of pitches measured at the same radial distance from the axis. (See also *lead deviation*.)

Cyclic error is an error that occurs during each revolution of the element under consideration.

Lead deviation is the difference between the design lead and the measured lead or helix. Since the lead should be equal to the axial pitch multiplied by the number of threads, this also provides a check on the axial pitch. (See also *cyclic error*.)

Profile deviation is the difference between the design profile and the actual measured profile. With an involute helicoid thread form, this setting is derived from the base diameter and the base lead angle.

Transverse pitch deviation is a measurement taken from one pitch to the next at the same radial distance, but at right angles to the axis, in a worm with a number of threads greater than one. This provides a check of the accuracy of the divide mechanism in the thread finishing process.

The Worm Wheel. *Adjacent pitch deviation* is the difference between the design pitch and the actual measured pitch of two adjacent pitches. The maximum adjacent pitch error will be that which occurs where the difference between the ideal and measured pitch is the greatest of the pitches tested around the circumference.

Cumulative pitch deviation is the difference between the design dimension and the actual measured dimension of any two teeth more than one pitch apart. The number of pitches to be covered is usually stipulated, and the error will be the algebraic sum of the adjacent pitch errors of all the intervening teeth taken over that number of teeth over which the maximum deviation occurs. This value will also take account of eccentricity, which of itself increases cumulative pitch error.

Profile error in a worm wheel tooth flank is imposed by the cutter with which the gear is generated. Since the shape of the profile changes at each position across the flank of the teeth, measurement is not practicable, and the correctness of this depends almost totally on that of the cutter and the setting. Frequently a gear manufacturer will modify the profile in order to provide a facility for deflection and the ingress of lubricant, so the shape may intentionally vary from that of the worm.

Measurement

Worm shaft. The deviation in pitch and lead of a worm can be ascertained by mounting the component between centers in a test machine and then positioning a stylus touching a flank in the same horizontal plane as the axis. The probe is loaded and set to move parallel to the axis as the worm is rotated. The two movements are coordinated so that the probe follows the path of the true lead. Any inaccuracy in the lead will move the stylus, which causes the relative movement to be registered and recorded in the control system.

Fig. 1 shows diagrammatically the main components in a modern lead test machine where the rotary and linear gratings are coordinated through the processor or control system, which produces the results in the form of a graph and any error values in microns. The machine of this type used at Holroyd was designed and built in-house and is capable of measuring lead and, therefore, pitch to an accuracy of 1 micron. It is described in greater detail in the section dealing with single flank testing.

Transverse pitch deviation can be obtained by mounting the worm in a pitch testing machine, as shown in Fig. 2, with the stylus set to a position about half way down the flank, and the incremental divisions set to the number of threads in the worm. The stylus will then enter and, after contacting the worm flank, retract until the next flank is available. The stylus will register the position and possible deviation of the flanks, which is a function of the amount of the deflection of the stylus. The machine at Holroyd will measure pitch errors "on the fly," that is, while the component is rotating continuously, with the stylus being inserted and withdrawn automatically.

The profile can be checked as shown in Fig. 3, where a stylus is set to the root of the worm thread at a position offset from the axis at a radius equal to the base radius and at an angle equal to the base lead angle. When the worm is held rigid, it should be possible to draw the stylus along the flank, scribing a straight line. Any deviations that register on the dial gage indicator or meter are dimensional errors in the profile.

Worm Wheel. When confirming the adjacent and cumulative pitch errors in a worm wheel, it is necessary to mount the component on the spindle or table of a pitch test machine and ensure that it is concentric by reference to a location or diameter provided for that purpose. As mentioned earlier, the machine functions by rotating the wheel and a stylus mounted in a position level with the center line of the component. As shown in Fig. 4, the stylus enters the pitch space and retracts when touched by the flank of each tooth. In this way, the position of each flank is registered relative to the position of the next, and when the full circumference has been covered, a picture is available through a processor that shows a full picture of each tooth position. The charts in Fig. 5

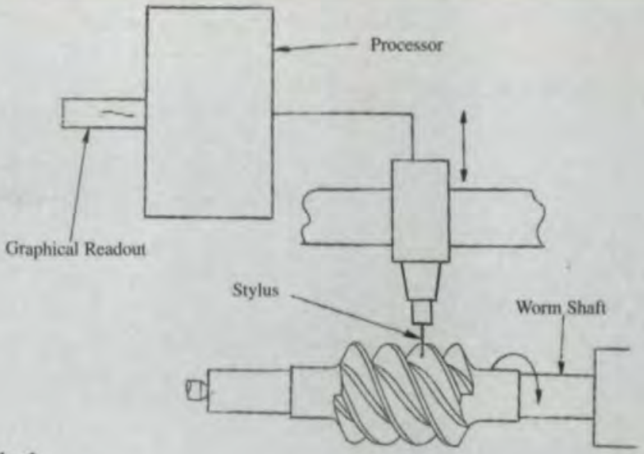

Fig. 2

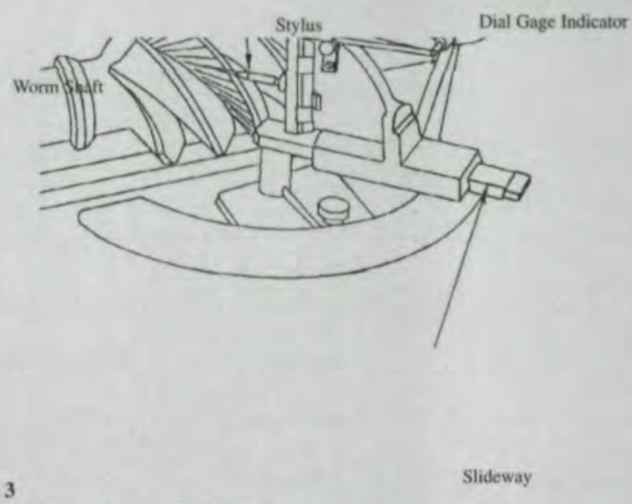

Fig. 3

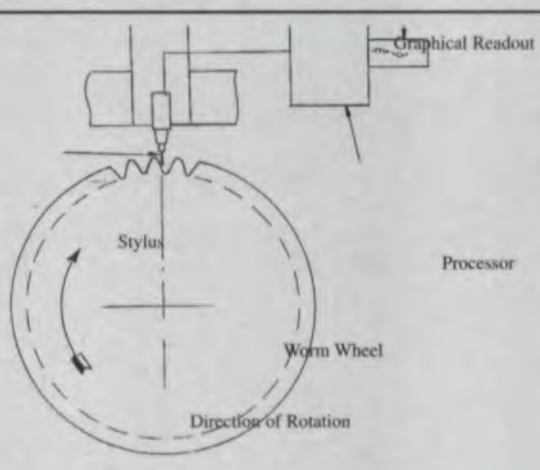

Fig. 4

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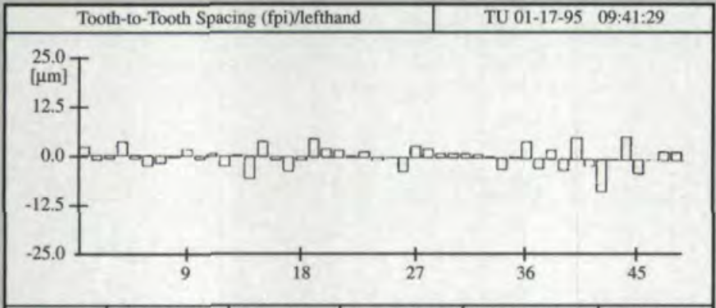
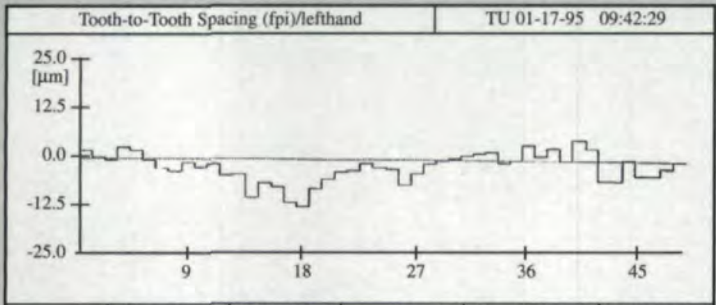


	Actual Value	Toler. Value	Actual Qual.	Nominal Qual.	Tol. Eval.
fpt	8.4	5.5	—	—	** 2.9**

Fig. 5a



	Actual Value	Toler. Value	Actual Qual.	Nominal Qual.	Tol. Eval.
Fp	17.7	10.0	—	—	** 7.7**
FP 24	2.5	10.0	—	—	+

Fig. 5b

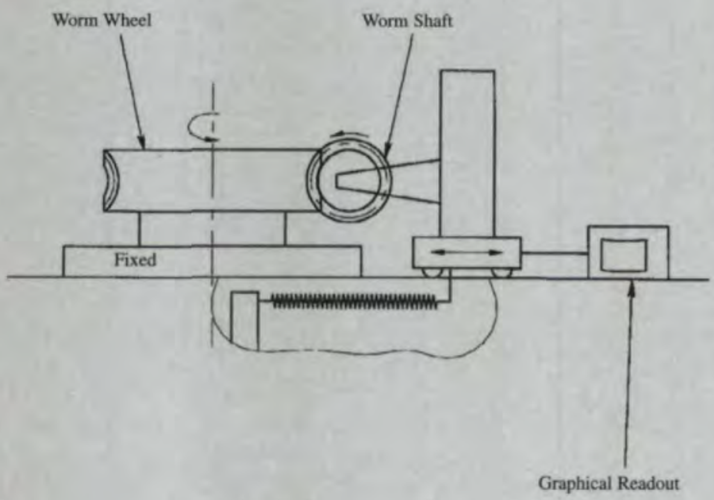


Fig. 6

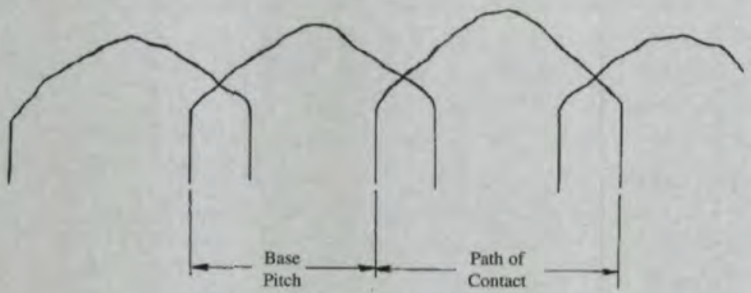


Fig. 7

illustrate an example taken from a 45-tooth worm wheel, 5a showing the tooth-to-tooth spacing errors and 5b the cumulative situation, which also demonstrates the eccentricity.

To check the compatibility of the profile with that of the mating or master worm, it is usual to assemble the two at correct centers in a test rig, apply Prussian blue to the worm thread and adjust the wheel axially until a contact marking, which is a mirror image of the one apparent on the opposite side of the tooth, is obtained on the flanks.

Worm Shaft With Worm Wheel. Backlash can also be confirmed in this operation by placing a dial gage indicator at one point of the worm wheel with the stylus loaded and located touching a flank of the component. By preventing movement of the worm and attempting to rotate the worm wheel in each direction, the inspector is able to read the full rotational movement possible, which is the backlash.

The operations outlined can be carried out in the machine area and, if errors outside the specification are detected, and there is sufficient material remaining on the component, rectification may be practicable. Even then, these procedures can only give an indication that the gear will fulfill the designer's requirements, the ultimate proof being a dynamic test with the worm and worm wheel assembled in a test machine that simulates the eventual operating position.

One intermediate test, which has been performed frequently in the past and which does enable limited dynamic testing of the assembled gears, is the double flank composite or rolling test. The composite error is defined as one revealed by measurement of a dimension that is influenced by two or more of the classic errors of pitch, profile and radial or lateral runout. This test consists of mounting the worm and wheel at the correct center and height setting in a machine, which is shown diagrammatically in Fig. 6.

The assembly is composed of a fixed spindle upon which the worm wheel is placed. The worm is mounted between centers in a carriage that is spring-loaded to exert a pressure to close the centers and is also connected to a recording processor.

Once assembled, the carriage is released so that the worm is thrust into the worm wheel, resulting in a double flank contact. As the worm is rotated, it will move in or out of centers, these movements being recorded in the processor.

This test does identify variations in tooth thickness and the effect of errors, but does not facilitate the identification of these errors, for example, whether movement is caused by variable tooth

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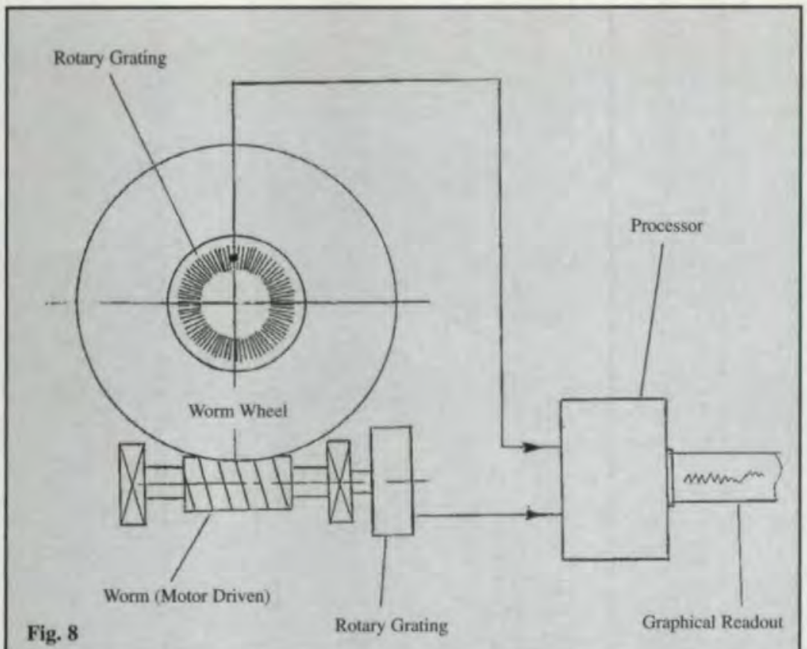

Fig. 8

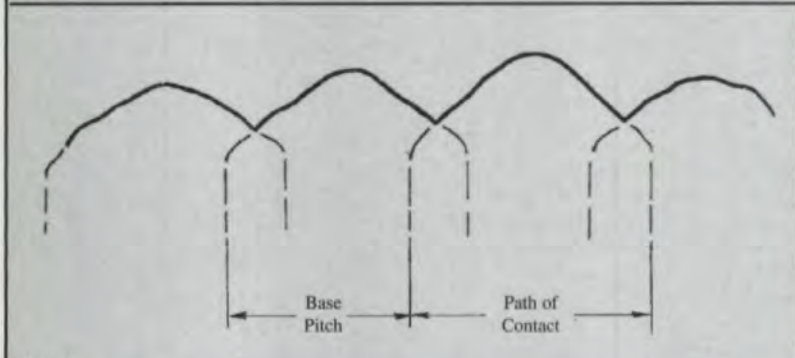

Fig. 9

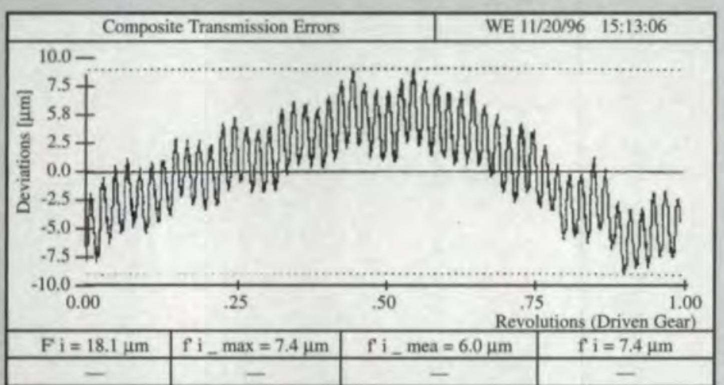

Fig. 10

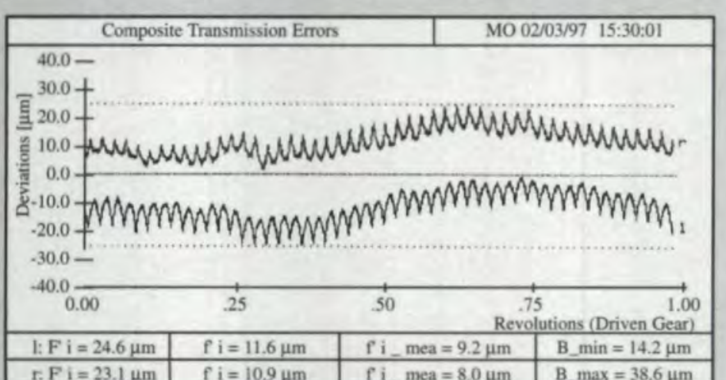

Fig. 11

thickness or an error of pitch. Also, it involves contacts on both sides of the teeth and threads, in which condition very few worm gear sets actually operate, and at closer than design centers, which of itself can introduce effective profile errors where, in fact, they may not truly exist.

Single Flank Testing

More detailed information can be obtained from the single flank or transmission method of testing, which operates from the principle that when a worm and worm wheel are assembled at correct centers, and the worm is rotated at constant speed, there is a slight change of speed of the worm wheel with each tooth engagement, as graphically illustrated in Fig. 7. This variation can be the result of pitch or profile errors in either the worm or worm wheel, cyclic errors in the worm or, accumulatively, eccentricity in the worm wheel, which shows as displacement of the base line.

Fig. 8 shows the principal features of a machine on which this test is carried out. With the worm shaft having center locations ground concentric to the bearing journals, the component is located between centers and is driven by a geared servomotor with a precision optical grating attached to the worm axis.

The mating worm wheel is secured onto a rotary table, which is supported by a hydrostatic bearing and also has a precision optical grating coupled to its axis.

When the worm is driven, the speed of the worm wheel would ideally be that of the worm divided by the actual ratio of the gears, but in practice there will be microvariations in speed due to pitch and profile errors in the waveform shown in Fig. 9. These are detected through the relative dispositions of the grating's registering signals through the central system, where errors to 1 micron can be identified.

The scale of these can be varied in order to increase or decrease the dimensional representation. An example, which is taken from a 50/1 ratio worm gear set, is shown in Fig. 10.

These values are in terms of linear measurement, but by knowing the pitch or reference diameter of the worm wheel along which contact takes place, they can be easily translated into angular measurement in seconds of arc by use of the formula $412 \cdot 5F/d_2$, where F is the error in microns and d_2 the pitch diameter of the worm wheel in millimeters.

It is necessary to perform the test with a small amount of backlash present so that no contact with the nondrive flanks can occur, which otherwise would lead to incorrect results. Particular care is necessary here with the dual lead or duplex type worm gearing, where backlash can largely be adjusted out to ensure clearance is present. Having carried out a recording of values for one direction of rotation, the directions can be reversed, and the procedure repeated in order to obtain values for the opposing flanks.

This method of gear measurement provides significant benefits to both the gear manufacturer and the customer.

For the manufacturer, the pitch-to-pitch probe test confirms the position of each tooth relative to its partners, which serves as a check on the accuracy of the production machine, but, unlike with the worm, it is not practicable to check the tooth form other than by a contact mesh test with the mating or a master worm.

Since the single flank test takes place with the gears in mesh with several teeth partially in engagement, the effect of individual adjacent pitch errors may be negligible, and a more accurate assessment of the ultimate performance is possible.

The influence of deviations in profile can be identified and in certain circumstances reduced by modifying the profiles of the worm threads, this being a relatively simpler operation than recutting the worm wheel.

A long-term solution to this problem would be for a consideration of the methods of manufacture and accuracy of grinding the worm or of the hob or cutter employed in generating the teeth of the worm wheel.

It might also be practical to increase the number of teeth in the worm wheel to ensure that a greater proportion are in instantaneous engagement, since where a component contains a relatively small number, the deviation recorded for the profile may exceed the effect of pitch and concentricity errors.

For the user, the information derived provides information relative to the likely dynamic performance. The waveform can indicate the degree of uniformity of motion, which will have a considerable bearing on the likely noise level at speed, or it will confirm the positional accuracy to which adjacent and accumulative pitch errors can only give guidance.

For example, having this information and knowing the start/finish position of the worm wheel in the test, the builder of CNC indexing or rotary tables can enter these values in the controlling software as a means of self-correction.

A further benefit of this system is that when performing the test for both directions of rotation, the results of the second or reverse operation can be reproduced onto the results of the first, as demonstrated in Fig. 11. When the upper limit line of the first test is positioned to coincide with the lower limit line of the second, the distance according to the scale between any two points on the curves in a vertical axis is the backlash. If the curves were to overlap at any point, this would represent interference.

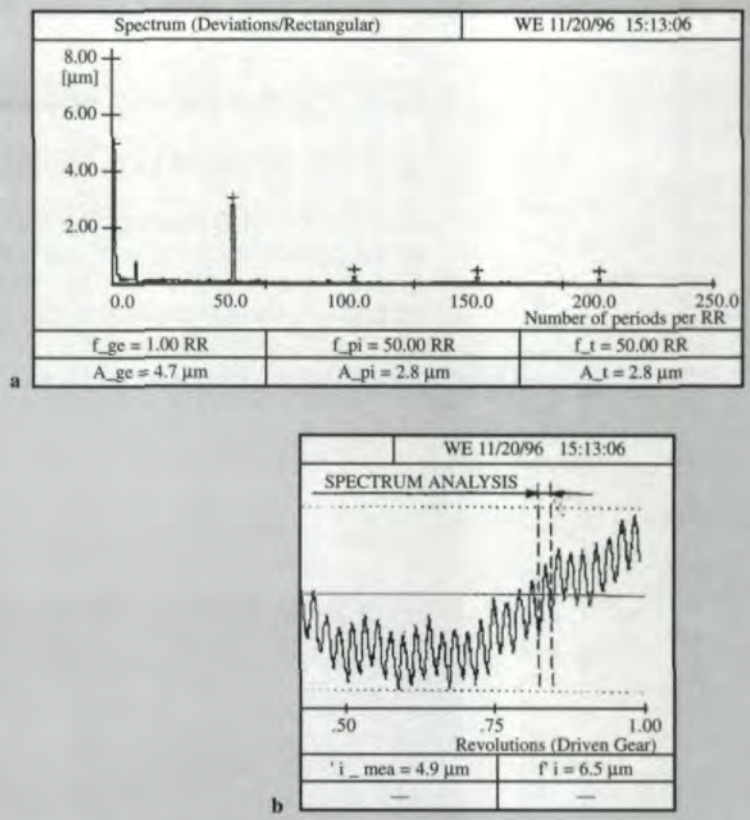

Fig. 12

In the example shown, the major cause of deviation of the curves is eccentricity, and it can be seen how this can influence backlash, a particularly important feature where the worm gears are required to operate in a situation when this has to be closely controlled or adjusted.

The facility also exists to carry out fast Fourier transformer spectrum analysis on the wave form, the results being quantified in Fig. 12a.

The baseline represents a number of periods of frequency over one revolution of the gear. The highest deviation occurs once per revolution, and in the case of this example, that will be the effect of the eccentricity. There is then a second major deviation at 50.00, which, with a 50-tooth worm wheel, represents each tooth engagement. Further smaller deviations occur at greater frequencies, representing a breakdown of the various characteristics of one "spark" or engagement, taken from the transmission test results, as shown Fig. 12b.

Information from this source can be invaluable when analyzing noise or vibration levels in a gear unit, for example, at high rotational speeds and in elevator machines. ○