Recent Developments in Gear Metrology

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Summary: Metrology is a vital component of gear manufacturing. Recent changes in this area, due in large part to the advent of computers, are highlighted in this article by comparison with more traditional methods.

Introduction

Various deviations from the true form of circular gears limit their ability to transmit uniform angular velocity at their designed speed and power. These deviations or errors are introduced during the production of the gear elements. The ability to measure these variations enables their magnitude to be determined and controlled during manufacture.

The various possible errors occurring in circular gearing are:

- Tooth Thickness (Backlash)
- Run-out Errors
- Pitch Errors
- Tooth Form Errors
  - profile
  - alignment
  - surface finish.

The types of circular gears in common use which can exhibit some or all of the above errors are involute spur and helical gears and bevel gears, both straight helical and spiral bevel.

This article will concentrate on involute gearing; however, some comments on bevel gears will be made.

The ability to measure the errors present in the various cutting tools, such as hobs, shaping cutters, and shaving cutters, as well as the gears themselves, is also useful.

Traditional/Classical Instruments

In order to highlight the advantages of the latest developments in gear metrology, a brief summary of the traditional/classical instruments used to measure the various gear errors will be presented first. The reader is referred to the various texts and papers listed in the bibliography for more detailed information.

Tooth Thickness. Three main methods have been prevalent in the measurement of tooth thickness of involute gears.

The first method involves the use of an instrument called a gear tooth caliper (Fig. 1). It consists of a depth gauge, which is used to set a known distance down from the outside diameter of the gear, and a caliper to measure the tooth

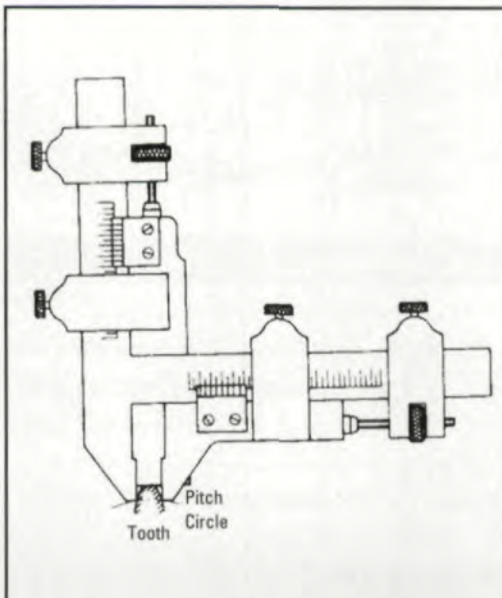

Fig. 1 - Gear tooth caliper

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thickness at this depth. Calipers are available for modules 1 mm to 50 mm.

This tool has the following disadvantages:

a) It relies on an easily worn, very sharp edge at the end of the caliper jaws to accurately measure the tooth thickness.

b) It relies on the outside diameter of the gear for its datum.

c) It relies on operator skill.

d) It is limited to about .001"- .002" accuracy.

This method's advantage is that it is inexpensive.

The second method uses the flange micrometer and is called the base tangent method. This instrument takes span measurements across a number of teeth (Fig. 2), which are then related to the actual tooth thickness by the involute geometry of the gear. Micrometers can measure modules from 0.5 mm to 11 mm.

The main disadvantages of this method are:

a) Pitch errors can influence the result.

b) Profile errors can influence the result.

c) Tip or root relief may make a valid measurement impossible.

d) It relies on operator skill.

The main advantages are:

a) It is more accurate than the gear tooth caliper.

b) It is not influenced by variations in the outside diameter of the gear.

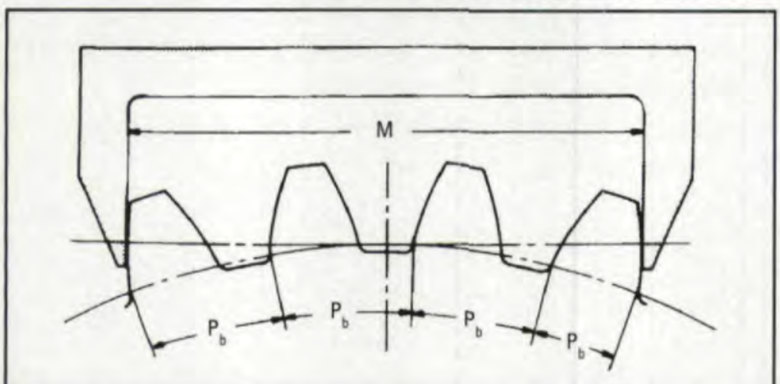

Fig. 2 - Span measurement of tooth thickness

The third method involves "measurement over rollers", where two rollers are placed on opposite sides of the gear, and the distance across these rollers is measured (Fig. 3). This value can be related to tooth thickness by the known geometry of involute gearing.

This method has the following disadvantages:

a) It is limited to gears small enough to be spanned by available micrometers and the available sizes of rollers.

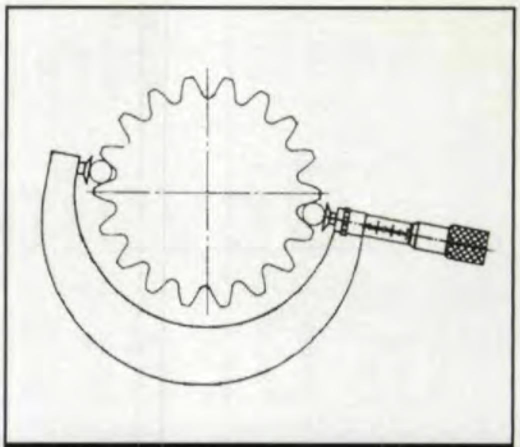

Fig. 3 - Tooth thickness measurement over rollers

b) The measurements are affected by errors in tooth spacing and profile.

The method's advantage is that it is not influenced by variation in the outside diameter of the gear.

All of the above methods are manual and require skill and dexterity. As such, they are not suitable for the measurement of all the teeth on gears with large numbers of teeth or on gears made in large quantities. The methods are most suitable for spot checks in small batch production situations.

Other methods available are:

1) Measurement of center distance at tight mesh. (See section on Dual Flank Rolling.)

2) Measurement of backlash at operating center distance. This method requires the ability to accurately assemble the gears at their nominal center distance with axes parallel.

Run-Out Errors. Radial run-out errors are defined as "the total range of reading of a fixed indicator, with the contact point applied to a surface rotated without axial movement, about a fixed axis, and measured perpendicular to the axis of rotation." The eccentricity is then also available, as it is half this radial run-out.

This type of error traditionally has been measured by inserting a ball (or cylinder) into each tooth space, and measuring the radial variation in distance from the center of rotation to the ball (See Fig. 4.).

Radial run-out measurements made in this way also reflect variations in tooth thickness. When radial run-out readings are plotted, the influence of each factor can be seen. Run-out errors are seen as a smooth, sinusoidal variation, while tooth thickness variations are seen as

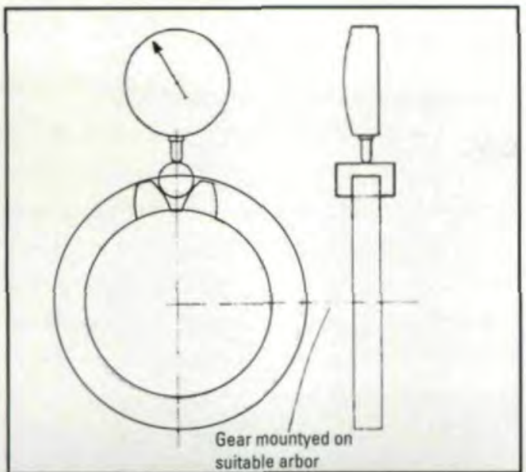

Fig. 4 - Measurement of radial run-out

fluctuations about a smooth curve drawn through all readings.

There are also automatic testers available which measure this error on a continuously rotating gear and plot the resulting error graph. These testers are available for module ranges of 1 mm to 40 mm and 0.1 mm to 20 mm respectively.

The double-flank rolling test can also be used, since in this test the run-out error is evident as a sinusoidal shaped variation with a period equal to one revolution of the gear. (See section on Dual Flank Rolling Test.)

Pitch Errors. The three types of pitch errors on spur and helical gears are pitch variation (deviation), fp; tooth-to-tooth pitch error, fu; and cumulative pitch error, Fp.

The classic method of measuring the cumulative pitch error is the index method, in which the gear is mounted on an angular dividing head (Fig. 5). The gear is then rotated through the nominal angular pitch, and deviations of each tooth relative to the first are noted and plotted.

The next more common pitch error measured is the tooth-to-tooth pitch error. This error is the change in pitch between successive pairs of teeth. As such, any instrument which can measure the change in pitch from one pair of teeth to the next can measure this error. A hand-held instrument that can do this is the Maag pitch measuring instrument type TIC. These instruments were available for normal modules ranges of approximately 2 mm to 10 mm. However, being hand-held and operated, this becomes a very tedious test on gears with more than a limited number of teeth. Automatic versions of this tester have been available for at least 20 years, and these testers measure the tooth-to-tooth pitch errors on continuously rotating gears

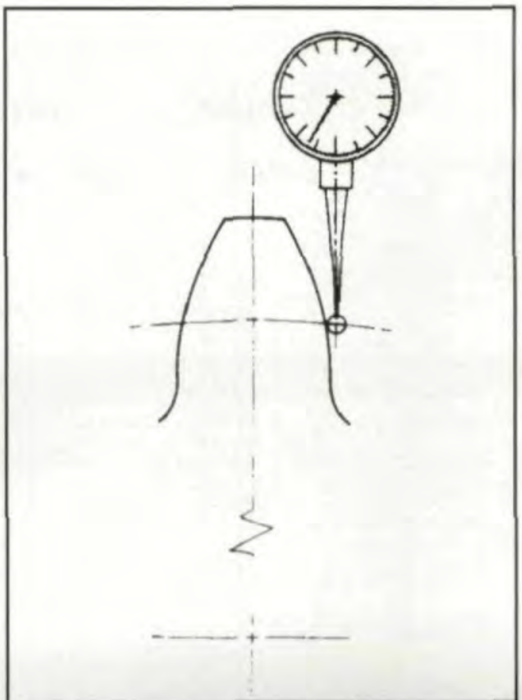
Fig. 5 - The index method of finding pitch error

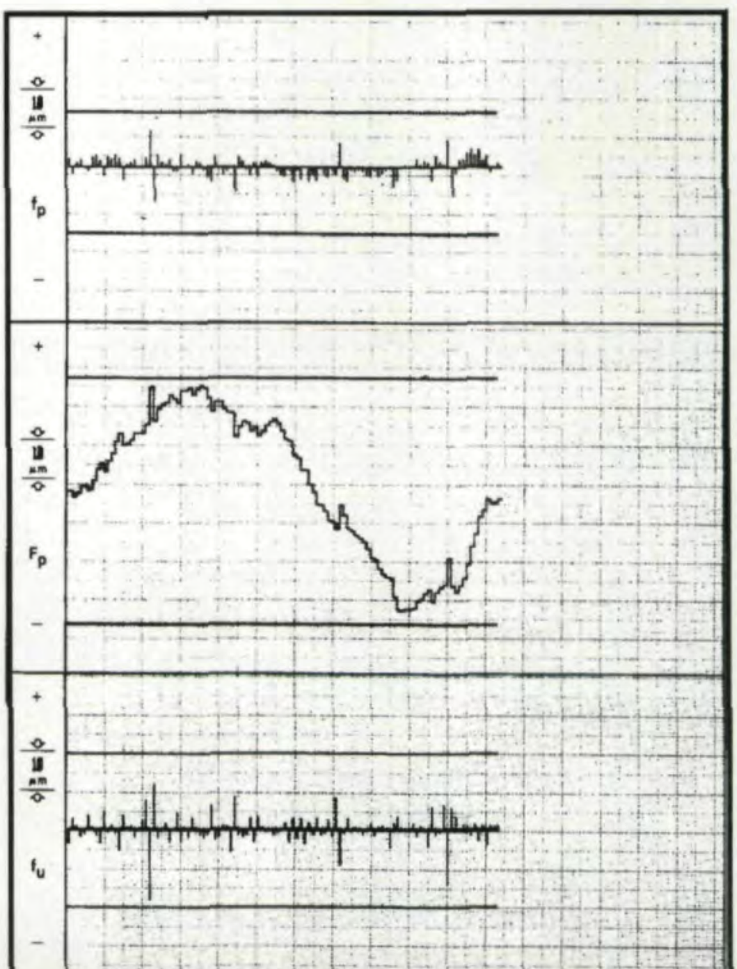

Fig. 6 - Printout of pitch errors

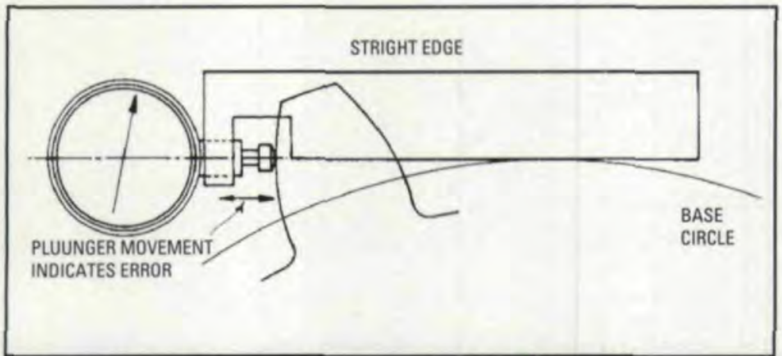

Fig. 7 - Measuring profile errors using base circles

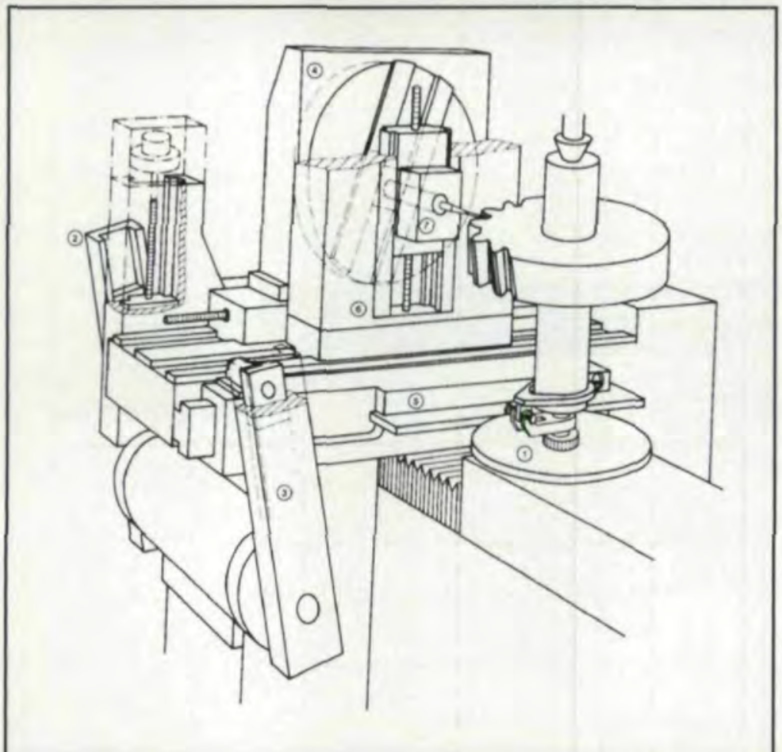

Fig. 8 - Lead and profile measuring machine

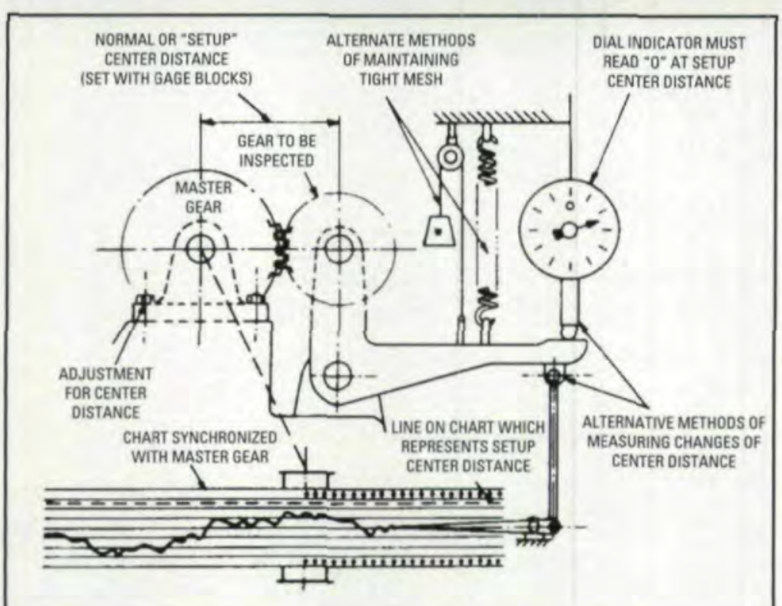

Fig. 9 - Dual flank rolling test

by inserting two probes to measure the tooth-to-tooth pitch error for that pair, and then retracting the probes until the next pair comes into position.

Pitch variation errors require measurement of the absolute pitch between two teeth and comparison with the nominal pitch. The Maag pitch measuring instrument mentioned above is capable of doing this test as well as the tooth-to-tooth test. It must, however, be set to the nominal pitch using gauge blocks or a setting master.

All of the above errors can be related mathematically (Ref. 8). This fact, coupled with recent advances in computer technology, has allowed the automatic pitch testers described here to measure the tooth-to-tooth pitch error, calculate the other two pitch errors, and plot all three for a complete picture of the pitch errors of the gear under test. (See Fig. 6).

The tester must understand that pitch errors and run-out errors are inseparable when present. If run-out errors are either introduced or removed during the test, the pitch errors measured will not give a true representation of the gear's actual performance in its final location. As the hand-held pitch measuring instruments do not refer their measurements to an axis of rotation, the resulting pitch errors are not affected by measurement-process-induced run-out errors. However, run-out errors present during manufacture will be evident as pitch errors on the gear. Pitch testers, in which the test piece is mounted and rotated about an axis, will be affected by run-out errors introduced or removed in setting up the test.

Profile Errors. Actual measurement, as distinct from contact bearing patterns of profile error, has until recently been limited to involute gears. Bevel gears, especially of spiral form, have not been measurable from first principles.

Because of the definition of the involute, profile checking machines have been available for many years. The early testers relied on the use of base circle discs for each gear to be checked (Fig. 7). Later machines overcame this limitation by the use of various mechanisms to either bridge the gap between a limited number of base circle discs or to eliminate them completely (Fig. 8). These testers all generate the true involute on a probe which is in contact with the gear tooth under test. Deviations in involute profile are detected by the probe and recorded for later analysis.

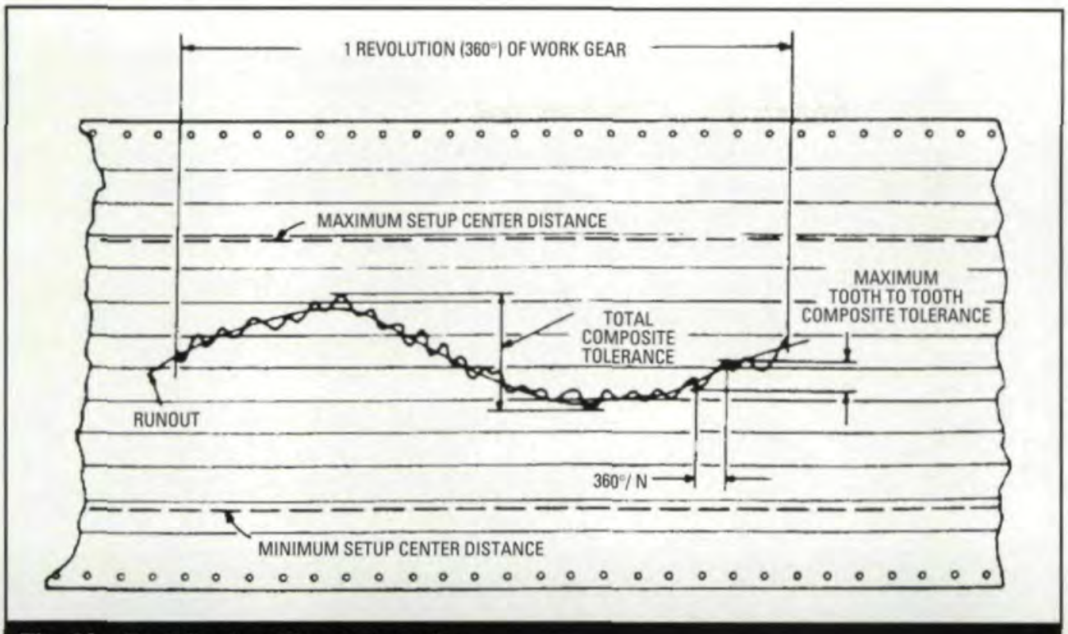

Fig. 10 - Dual flank rolling test results

Advances in computer technology have enabled the recording of the involute errors in digital form. This in turn allows computer analysis, which eliminates the weakest link in the measurement process: the human interpretation of the error curve. The use of mathematically rigorous techniques for this analysis can give an unbiased and consistent interpretation of the results.

The accuracy of these machines can be determined by well-understood tests on their geometry and construction. Because the software does not control the accuracy of generation of the involute on the probe tip, it is only necessary to test the software against known masters to verify its accuracy.

Alignment Errors. Alignment errors are often referred to as lead and/or helix errors. These errors have also been measured for many years on involute testers, modified with the necessary mechanisms to generate the nominal lead motion on the probe. The probe then detects variations in the same way as for the involute errors. Error analysis has been enhanced by the use of computer technology in exactly the same way as for involute errors.

Surface Finish. This feature has been measured by the use of surface finish testers. In some cases, these testers have been fitted to involute/lead testing machines to allow easier testing of gear tooth surface finish.

Meshing Tests. Meshing tests are functional tests to determine the actual performances of a gear or gear pair. These tests fall into the sections on dual and single flank rolling tests.

Dual Flank Rolling Test. In this test, the gears are brought into tight mesh so that both flanks are in contact. (Fig. 9) One gear, usually a master gear, is mounted on a fixed shaft. The other gear is mounted on a shaft constrained to move in a radial direction. As the gears are rotated, the variations in center distance are measured and often recorded.

This dual flank rolling error or composite error is then a combination of all the primary errors already discussed above. A plot of this error normally has two major components (Fig.10). The low frequency component is most commonly associated with run-out errors, while the high frequency component is associated with pitch errors. Because a composite error is generated, this test is only useful as a go/no go test. It is not good for identifying individual errors, and subsequently, rectifying a particular process.

Single Flank Rolling Test. In this test, the gear pair are positioned at their nominal center distance. The relative angular motions of the two gears are then measured. For a perfect gear pair, the motion of the output gear would be uniform relative to that of the input gear. Any errors would be reflected as a non-uniformity in angular motion on the output gear.

Because the gears are mounted at their nominal center distance, only one flank will be in contact. Also one gear needs to be driven while the other is braked. This test, therefore, comes

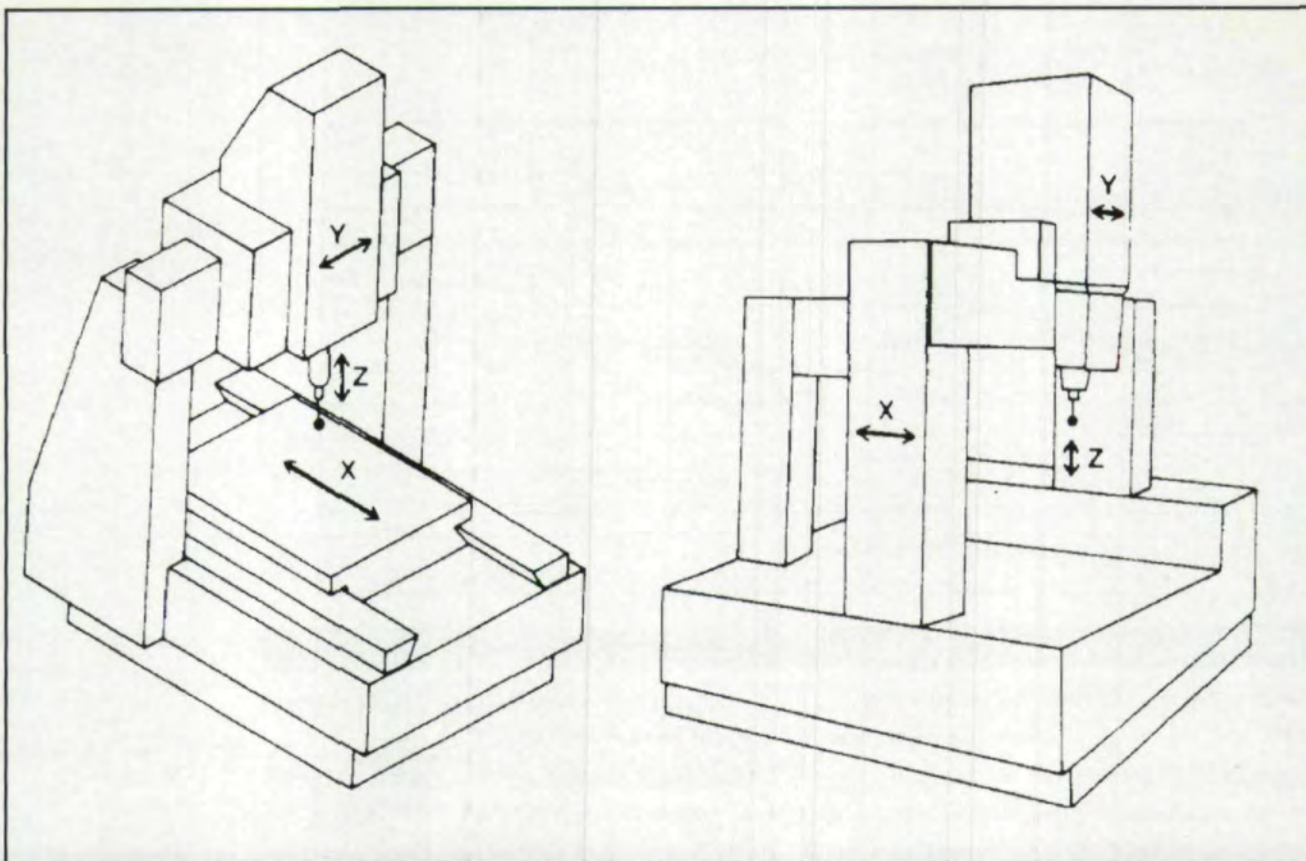

Fig. 11 - General purpose three-dimensional coordinate measuring machine

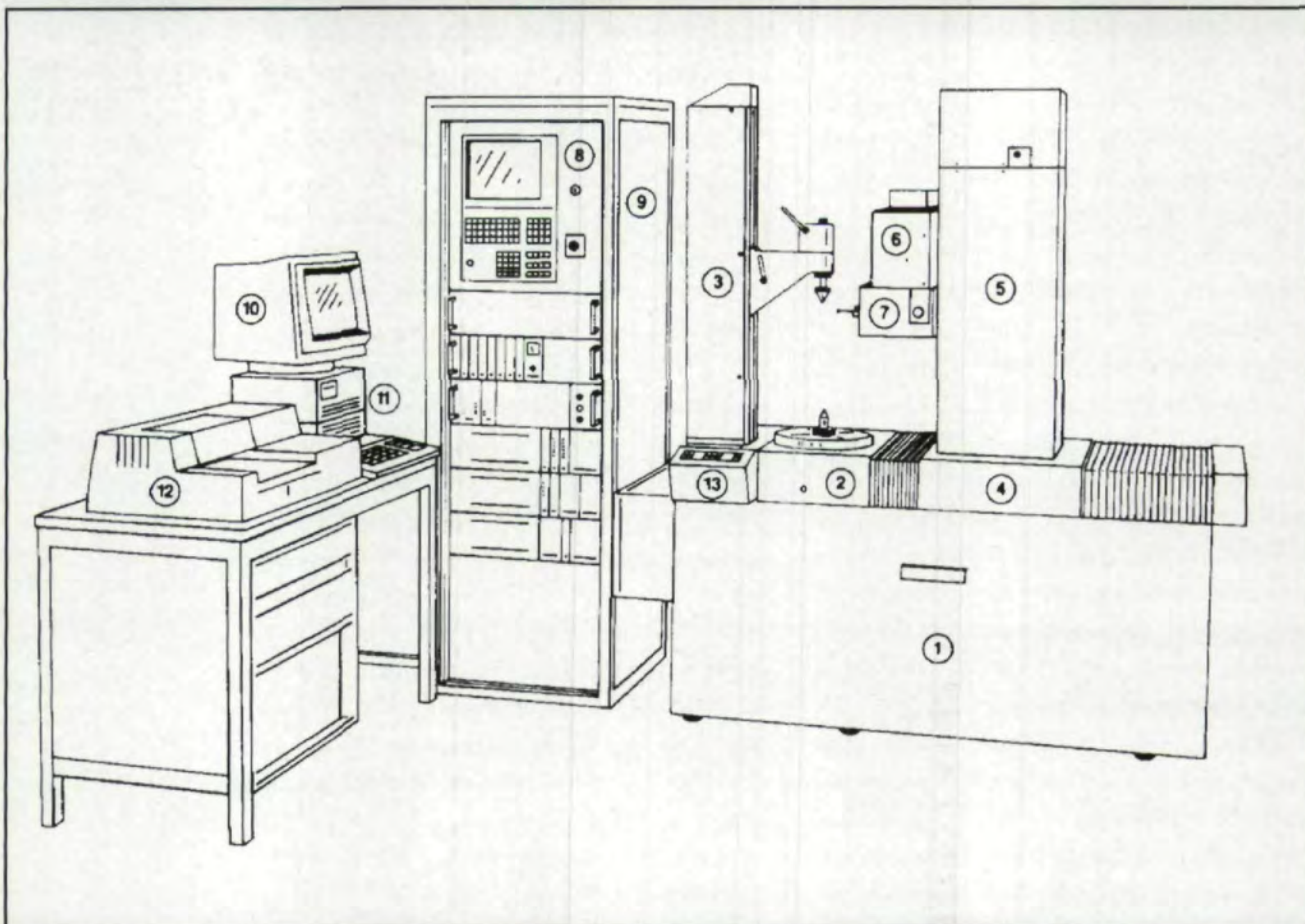

Fig. 12 - Gear measuring machine

very close to the actual operating conditions of the gear under test.

In the past, the difficulties involved in comparing the relative rotary motions of two rotating gears has meant that this test, although theoretically desirable, was physically impractical.

New Developments

The major changes in gear metrology have been brought about by advances in electronic/computer technology. The availability of large amounts of computing power in ever cheaper and smaller packages has spawned significant changes in all fields of technology.

The basic aims and principles of gear metrology have not changed. However, the methods by which these can be achieved have changed dramatically. These changes will be presented in the remainder of this article.

CNC 3-D Measuring Machines. The last 5 to 10 years have seen very rapid developments in the versatility of the computer numerically controlled, three-dimensional co-ordinate measuring machine (CNC 3-D CMM). Computers are becoming faster, more accurate, and have larger amounts of affordable memory in the form of volatile, random access memory, (RAM) and permanent (hard) discs. Therefore, the software on which all 3-D CMM's rely has become more and more sophisticated.

In this light, there has emerged two groups of CNC 3-D CMM's. The first is the general purpose machine (Fig. 11), which is primarily designed for the measurement of components that are not necessarily circular in nature. These machines are able to measure gears, but at a cost in speed and efficiency of measurement. This is because these machines have heavy and cumbersome arrangements for moving the measuring probes to allow for many variations in workpiece shape and orientation.

The second class of CMM's has been designed specifically for the measurement of solids of revolution. This allows the designer to tailor the machine to measure this class of workpiece much more quickly and efficiently than the universal type of CMM (Fig. 12). Machines are available to cater to gear diameters from 5 mm up to 2.6 m. They can also be used to measure general types of workpieces, but due to their specific design, this is slower and more difficult than for the general purpose type of CMM. Both of these testers can have 4 axes; three orthogonal and one rotational.

Therefore, a general rule can be stated: if mostly non-gear type components are to be measured with only occasional inspection of gears, a universal type of 3-D CMM is applicable. The reverse holds true if the major amount of work for the 3-D CMM is gear inspection. Also, due to the small tolerances generally present in gear specifications, only the more accurate versions of general purpose 3-D CMM's should be considered for use as gear measuring machines.

The new 3-D gear measuring machines (GMMs) are, by their very nature, computer controlled. They also rely on CNC for controlling the motion of the measuring probe. This type of control allows each machine to measure a number of parameters on the workpiece. This is in contrast to the previous generation of machines, which by their mechanical nature, were only able to measure one or, at most, two parameters. Now it is possible to place a gear on one of these new 3-D GMM's and instruct the tester to measure all of the primary parameters for that gear without further human intervention. This results in major time savings for any given level of thoroughness of gear measurement. The automation of the test sequences is even more useful when coupled to automatic loading facilities in large batch evaluation.

All measurements are processed in digital form, and this immediately allows the storage of these results for comparison with later batches. These statistical process control (SPC) abilities are a major advance, especially for manufacturers of large quantities of gears.

Also, some of these new 3-D CMM's and GMMs can measure other forms of gearing, with the addition of the appropriate software packages. The most notable advance has been the ability to measure spiral bevel gears in such a way that information relation to the actual corrections to the production machine settings are available. This can only lead to better bevel gears with, one hopes, more interchangebility than was available in the past. The ability to measure the condition of the various gear cutting tools (shaping, shaving, and hobs), again via the addition of software modules, also increases the usefulness of the GMM to the owner.

For similar expenditure, the purchaser of the

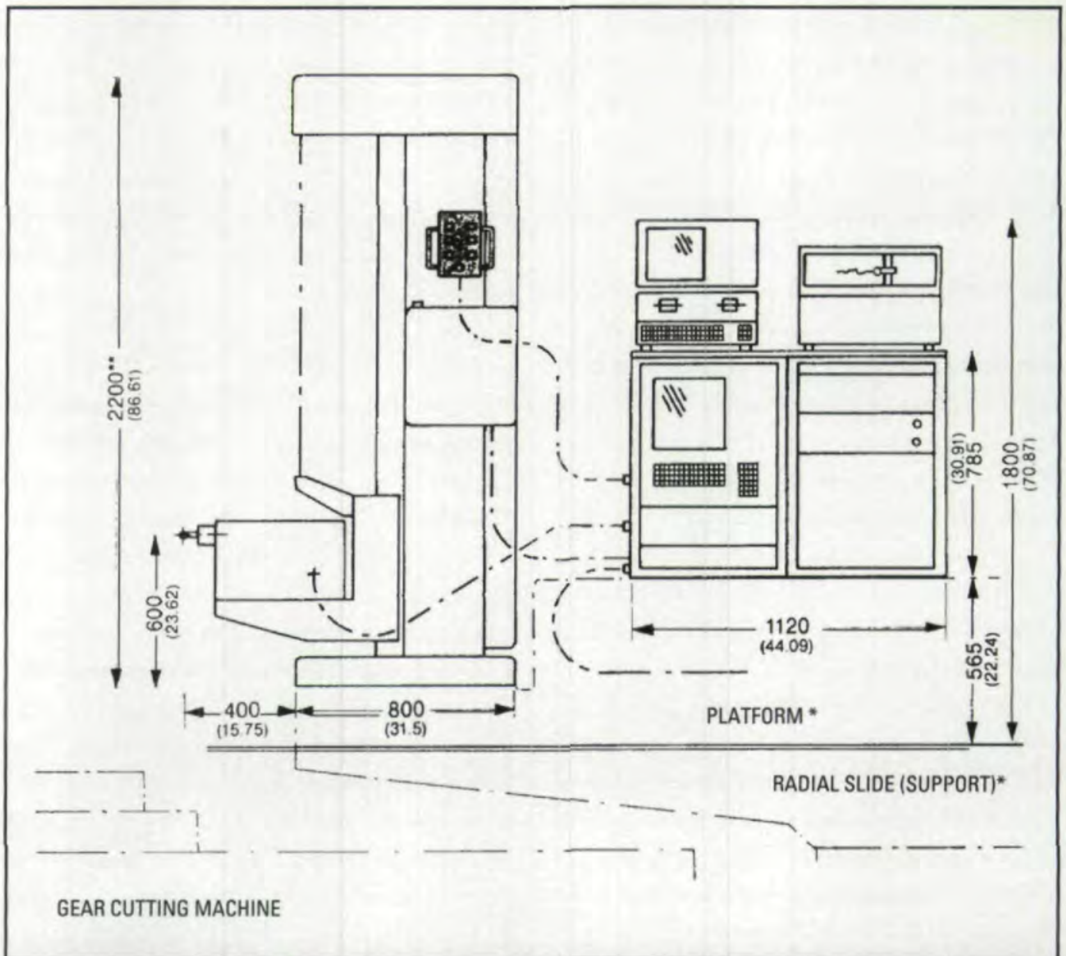

Fig. 13 - Transportable gear measuring machine

modern CNC 3-D GMM, obtains a machine with vastly increased performance and flexibility over the previous mechanical machines.

The verification of the accuracy of these machines requires the measurement of not only the mechanical accuracy of the machines, but also the accuracy of the CNC software control which actually generates the theoretical profile of the gear under test. This is in contrast to the generation-type machines described in the sections on profile and alignment errors, which generate these profiles mechanically. On the new machines, interactions between the CNC control software and the computer evaluation software needs to be understood and thoroughly checked.

Transportable CNC Lead/Involute Testers. Another development closely associated with the development of the fixed CNC controlled 3-D GMM described in the previous section is the transportable CNC lead/involute tester.

The largest fixed 3-D CNC GMM can accept gears up to 2.6 m in diameter. In the heavy engineering field many gears are larger than this maximum, and the measurement of the lead and involute profiles on these gears has previously not been possible.

The transportable gear measuring machine consists of a 3-axis CNC gear measuring machine which is designed to be fitted to the gear production machine tool (Fig. 13). This effectively allows the measurement of any gear diameter capable of being produced with modules in the range of 2 mm to 40 mm.

The transportable gear measuring machine can also measure gears on a large surface plate if necessary. The development of this tester has finally lifted the limit placed on gear metrology by the largest available dedicated testers.

The comments on verification of fixed 3-D GMMs apply equally as well to these testers.

Pitch/Run-Out Testers. As discussed in the section on pitch errors, automatic pitch and run-out testers have been available for at least 20 years. These testers were able to automatically measure the pitch errors on both tooth flanks as well as the run-out error present on a gear. However, this process involved three physical setups and passes around the gear.

The latest development in this area involves the ability of an automatic pitch tester to measure the pitch errors on both flanks, along with the run-out error in one pass of the gear. This results in a time saving on the order of 3, which becomes especially significant on gears with large numbers of teeth.

Rolling Testers. Advances in rotational and vibration transducers as well as in digital signal processing have resulted in improvements in this type of testing. The dual flank rolling test wave form can now be digitally analyzed to separate out some of the component errors, such as the detection and location of nicks, run-out, and tooth-thickness average.

The single flank rolling test, previously not effective because of signal processing limitations, has now become viable. Testers are now available which can detect nicks and the likelihood of gear whine, as well as measure the errors in angular velocity of the transmitted motion.

The angular velocity errors are further analyzed in the frequency domain to separate out the component frequencies contributing to the overall transmission errors. Further analysis to associate angular velocity variations with the number of teeth present allows each individual error component to be analyzed as a function of rotational speed. This gives powerful knowledge to the gear engineer, who can then use this information to eliminate the causes of gear noise and vibration.

Conclusions

Although the aims of gear metrology have not changed, the equipment and methods now available to the gear metrologist have given him/her very powerful tools with which to measure gears.

The new gear metrology machines can measure many, if not all, the parameters of a gear much more quickly and with more confidence than ever before. Measurements previously considered too difficult for routine application can new be performed easily.

Computers have played a major part in making these advances possible. They have made the control of CNC 3-D GMMs and CMMs possible, as well as the collection and storage of large amounts of data. Their unbiased assessment of this data, together with the clear presentation of the results, has given much faster and wider access to the results of gear metrology. This access has enabled much more effective action to be taken to minimize the errors found.

However, these advances should be tempered with caution, as the new machines are essentially only as good as the software driving them and the people operating them. It is very easy to have blind faith in impressively presented results, but a wary eye must be kept out for hidden sources of error. ■

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