Extending the Benefits of Elemental Gear Inspection

By I. Laskin

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Management Summary

It may not be widely recognized that most of the inspection data supplied by inspection equipment, following the practices of AGMA Standard 2015 and similar standards, are not of elemental accuracy deviations but of some form of composite deviations. This paper demonstrates the validity of this "composite" label by first defining the nature of a true elemental deviation and then, by referring to earlier literature, demonstrating how the common inspection practices for involute, lead (on helical gears), pitch, and, in some cases, total accumulated pitch, constitute composite measurements. The paper further explains how such measurements often obscure the true nature of the individual deviations. It also contains suggestions as to some likely source of the deviation in various gear manufacturing processes, and how that deviation may affect gear performance. It further raises the question of the likely inconsistencies of some of these inspection results, and of inappropriate judgments of gear quality, even to the point of the rejection of otherwise satisfactory gears. Finally, there are proposals for modifications to inspection software—possibly to some inspection routines—all to extending the benefits of the basic elemental inspection process.

Introduction

The gear industry, here in the United States and internationally, has adopted two systems of specifying and measuring the accuracy of gears: one is composite inspection, which recognizes that the inspection measurements are the result of a combination of accuracy deviations, generally derived when the test gear is engaged with some form of master gear; the other is generally labeled as elemental inspection, or sometimes as analytic inspection. This inspection system looks at individual elements of gear accuracy or, at least, attempts to do so, all as part of analyzing the complete nature of the gear's accuracy. This paper deals only with the system of elemental inspection, especially as performed by modern, computer-controlled inspection equipment. Not only is the inspection process itself computer controlled, but also the processing and reporting of the inspection results. This makes possible additional or alternate data processing, with results reported in a form that clarifies or enhances current forms of inspection data reporting.

AGMA Documents

Current U.S. practice in elemental inspection closely follows a pair of AGMA documents. AGMA 9151A02 (Ref. 1) describes a variety of tangential measurements, many adopted for use in so-called elemental inspection. The second, ANSI/AGMA 20151A01 (Ref. 2), defines the elemental version of a gear accuracy classification system based on selected tangential measurements described in the AGMA 9151 document. This specification of accuracy classifications introduces tolerances for each specified elemental measurement. These tolerances, in effect, determine whether the test gear meets specifications and, upon failure to do so, will lead to rejection and scrapping, or rework. If the test gear came from some kind of molding process, the rework could extend into the molding tool.

The system of elemental gear accuracy defined in Reference 2 lists the following eight items, along with the general inspection procedures which provide the measure-

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ment data for each. These will be reviewed in groups later in this paper.

1) Single pitch deviation
2) Cumulative pitch deviation
3) Profile, total
4) Profile slope
5) Profile form
6) Helix, total
7) Helix slope
8) Helix form

There is another set of AGMA documents that treats composite-inspection radial measurements (Refs. 3–4), but these measurements are not directly connected to the elemental measurements discussed here. There is one exception (Ref. 3), dealing with the subject often called "hidden run out," addressed later in this paper.

Objectives

The objectives of elemental inspection are threefold:

1) To compare the inspected gear to the gear accuracy specifications, which may have been stated individually or as a group by accuracy class.
2) To indicate what in the gear manufacturing process has caused the departure from ideal gear geometry.
3) To help identify the effect of the elemental condition on the performance of the gear.

In meeting all these objectives, elemental inspection has demonstrated its benefit to the gear designer, the gear manufacturer, and the user of the gear.

The objective of this paper is to: examine the elemental inspection process as defined by the referenced AGMA documents; to indicate where and in what way it may be improved in meeting the above objectives; and to propose changes that will provide such improvements. Success in this effort can be recognized as extending the benefits of elemental gear inspection.

Definitions

Although the following terms are used in the AGMA documents, their definitions are generally by inference, rather than by readily located statements. The definitions given here conform to the general usage of the terms, inside and outside of gear technology. They are generally in agreement with their use in the AGMA documents, with the possible exception of the use of elemental, as will be noted later.

Deviation: the dimensional departure from the geometry of the ideal gear, as defined, directly or by inference, in the gear specifications, including any design modifications, such as tip relief or face crown, introduced by the gear designer.

Elemental: any component of gear accuracy which cannot be further reduced to subcomponents and, as such, may be present alone or in combination with other elemental components. Elemental components are often associated with a single source in the manufacturing process and have an individual effect on gear performance.

Composite: any gear accuracy designation applying to a combination of elemental components.

Gear Manufacture

Gear accuracy definitions and measurements are independent of the method of gear manufacture. However, each manufacturing method may produce its own set of typical accuracy deviations, requiring its own set of measurement procedures. For example, wide-faced gears made by the powder metallurgy (P/M) process tend to have a hollow condition in their face width, namely—a smaller diameter at the face center with a larger diameter near the end faces. This will be revealed in the helical inspection trace. Any inspection for profile should then be made at the face-located, larger diameters because it is these gear sections that will interact with a non-crowned mating gear on the parallel shaft. It is the responsibility of the gear designer to specify such inspection locations.

It is important to recognize that each manufacturing method may also bring its own set of typical accuracy deviations. In the measurement and data analysis methods in use for one specific accuracy deviation, another type of accuracy deviation may insert itself. This could result in a composite measurement, rather than a true elemental measurement. Such a condition, in the form of "eccentricity of mounting," is mentioned in (Ref. 1), clause 7.5, and will be further discussed below.

Run out. Run out is applied to a variety of individual, elemental accuracy deviations, each associated in some way with a varying distance of individual gear teeth—or tooth spaces—from the datum center of the gear. None of these individual, elemental deviations is listed directly as part of elemental inspection requirements, but their presence often enters into almost all of the other inspection procedures. The effect of some kinds of run out on the results of these inspection procedures will be given extensive treatment in this paper as part of an effort at clarification and enhancement of the coverage in the AGMA documents.

Three types of run out will be discussed:

- **Eccentricity**—in which the center of the ring of gear teeth, which may itself be close to ideal shape, is offset from the datum center of the gear—the one center used for all gear measurements and likely to be used in the mounting of the gear in its application.
- **Out-of-round**—in which the shape of the ring of gear teeth is not round, so that even if no eccentricity is present, measurements from all teeth or tooth spaces would not be constant.
- **Hidden run out**—a condition in which eccentricity in the gear was present in an earlier step of manufacture but, in some later step, was modified so as to "hide" one of its negative features from some inspection processes.

Eccentricity. Regardless of the method of gear manufacture, there are likely to be cases in which the inspected gear has some degree of eccentricity. Examples of some of these are:

- In the case of a machined gear, it is common practice to locate the gear blank by its datum center in the form of a through-hole. Manufacturing variation in the size of the hole—especially when several gears are stacked on a single arbor, matched to the size of the smallest possible hole—will introduce eccentricity between the hole's datum axis and the ring of machined gear teeth, into at least some of the stacked gears.
- If the gear is located during machining through some type of tooling with built-in eccentricity, such eccentricity in that tooling will be transferred to the gear.
- If the gear is molded from plastic, there exist other possible sources of eccentricity. In the mold, the core pin which produces the datum center hole may have been positioned eccentrically to the portion of the mold that forms the gear teeth. This is even more likely if the two mold features are located in different mold sections—one fixed and the other movable during the molding machine operation. This would be common for the molding of a compound, helical gear.
- Even without mold construction errors, the gears in a multiple-cavity mold may experience different rates of cooling across angular locations in their faces, resulting in different local shrink rates and the introduction of eccentricity.
- If the gear is made by the P/M process, some significant degree of eccentricity is inevitable.The compaction tool, which gives the initial shape to the gear, contains punches which must slide axially, relative to each other. The core pin, which forms the datum hole, is surrounded by a punch in the shape of the gear, which must slide in the die that forms the gear teeth. For gears with more complex features, there may be additional, concentric punches that participate in the relative sliding. To permit this sliding, there must be some clearance between the various, enveloping punches. Under the extremely high compaction pressures, these punches are pushed to one side, forcing the core pin to become eccentric to the die, and with the resulting gear teeth becoming eccentric to the datum center hole. To correct for eccentricity in higher-quality P/M gears, it is common to mold the center hole undersize and then machine it to size in a later operation that corrects the eccentricity.

The presence of eccentricity may affect gear performance in a number of ways:

1. Eccentricity introduces a once-per-rotation, varying center distance with the mating gear, a sometimes critical deviation—especially in fine pitch gears—resulting in variation in backlash between the involute flanks of the mating gears. (*Note: Eccentricity is sometimes, as in AGMA 2002 (Ref. 5), translated into a variation in tooth thickness having the same effect on backlash, leading to a so-called functional tooth thickness. This substitution does not consider the following two other variation conditions.*)

—Variation during meshing, in tooth tip to root circle clearance, and variation in tooth tip to fillet curve clearance between mating gears.

—Variation, during meshing, in contact ratio between mating gears.

2. Eccentricity introduces a sinusoidal component in the transmitted motion between the mating gears, potentially leading to once-per-revolution dynamic forces—especially if the gears are rotating at very high speed in a gear system with high mass inertia components—a rare condition which, even rarer, may impact the gear noise produced.

3. For gear systems which have a need for precise position control at output, as in computer printers, where the transmitted sinusoidal component may lead to banding in the resulting printed image.

The conditions listed under item 1 are typically resolved by design modifications to remove any critically harmful effects on gear performance. Those listed under item 2 are rarely encountered, and only in special applications. It is therefore safe to conclude that some limited eccentricity in a manufactured gear is, by itself, acceptable to the gear designer. What is not acceptable, as will be explained below, is any misinterpretation of inspection results brought on by the composite presence of eccentricity.

Analysis of Inspection Data

Inspection data will be analyzed, as follows:

- Description of the inspection process and the data produced;
- Identification of any composite components at each inspection, examples of a source in gear manufacture, and, most important, their potential effect on gear performance;
- Proposals for separating the composite components into true elemental deviations, whether by changes to the inspection process or by additions to the software

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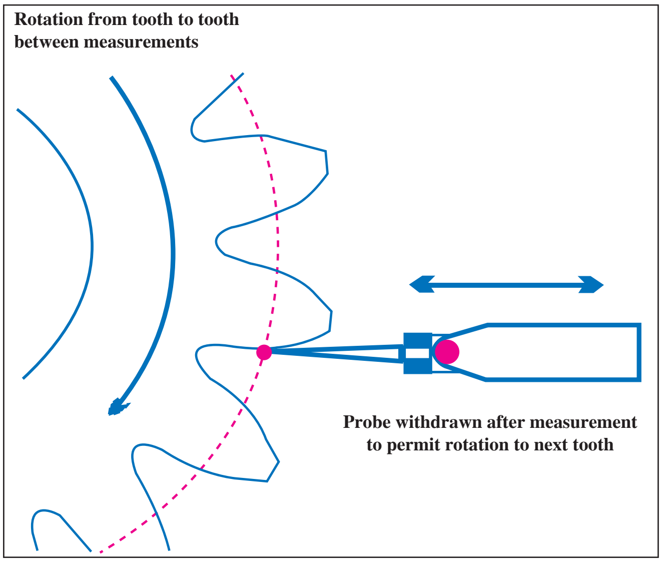

Figure 1—Measurement of pitch (or index) deviations.

that is to translate the inspection data to the preferred form.

The selected inspection items will start with those listed above as associated with the tolerances of the gear classification system. It will then move to additional gear accuracy conditions of potential interest to the gear designer, manufacturer, or user.

Pitch deviation, cumulative and single. The measurements for these deviations are made by indexing the gear about its datum axis through an angle exactly equal to the pitch angle—360° divided by the number of teeth (Fig. 1). At each indexed position, the measuring probe is inserted in a radial direction to the tolerance or inspection diameter, providing a probe deflection reading at the tooth flank. The deflection measurement is always made at the same diameter that will be centered on the datum axis. This process is then repeated for the opposite set of flanks. These readings, typically referenced to the first reading on tooth number one, are then plotted in a bar chart or stepped line, as shown in Figure 2. The full range of reading values for each flank is labeled "the cumulative pitch deviation," and the single-largest interval between successive readings is labeled "the single-pitch deviation."

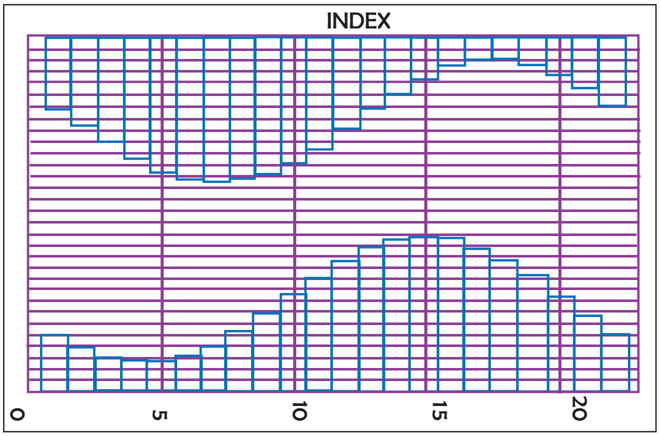

Figure 2—Pitch (or index) measurements on a gear with eccentricity.

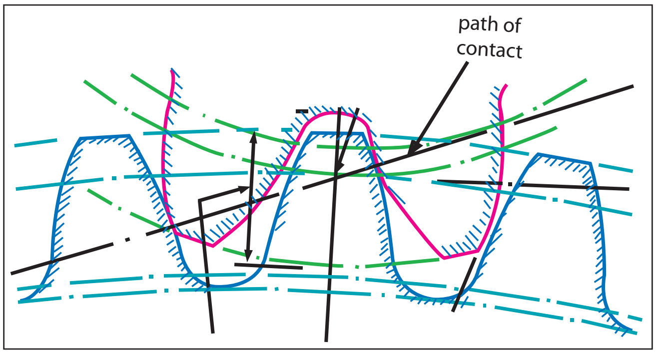

Figure 3—Transfer of contact at points on the path (line) of contact.

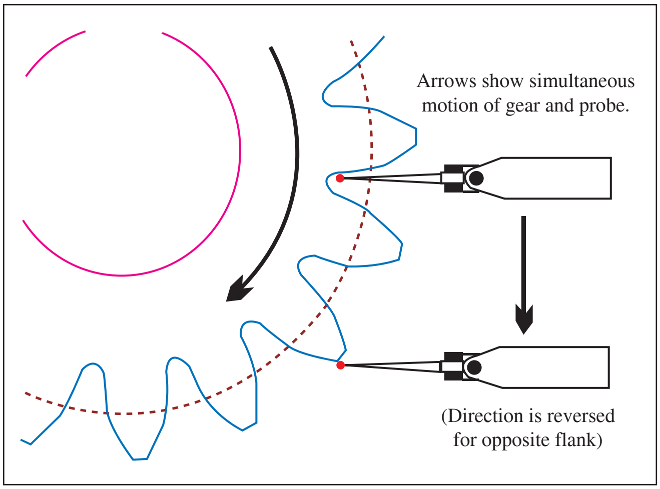

Figure 4—Measurement of profile (or involute) deviations.

The figure shows the plot for a gear with eccentricity as its dominant accuracy deviation. For each flank, the plot follows a once-per-gear-revolution mathematical sine curve. The amplitudes of the two sine curves are similar, but the apparent phase locations are noticeably different. There is a mathematically derived, and experimentally tested, relationship between the sine curve features and the eccentricity amplitude and direction (Ref. 6).

Even if the gear has other accuracy deviations that are essentially consistent around the gear—such as tooth flank pressure angle, incorrect tooth thickness, or helical gear helix angle—these curves do not change except for a possible, slight shift in the phase relationship of the two sine curves for the two tooth flanks. Therefore, the following evaluation of the information supplied for most gears with eccentricity will apply in each case:

- The cumulative pitch deviation reported by this inspection process does not provide any direct information about the gear's manufacture or performance. What it does do, indirectly, after applying the calculation noted above, is provide a measure of the eccentricity and its phase relationship to some reference on the gear. Yet, this eccentricity information, as important as it might be, is not directly included in the tolerances that define the gear's accuracy classification.
- The single-pitch deviation value reported by this measurement is directly, and even indirectly, essentially useless. What is generally needed from a tooth spacing measurement is an indication of how well the gear will transfer contact and load as one pair of mating teeth are replaced by the next pair. A smooth transfer requires that the tooth spacing of the two gears be closely matched (Fig. 3). Otherwise, any mismatch can result in added dynamic loads and gear noise. However, this mismatch to be judged is along the line of action in a base tangent direction, and not along the tolerance or inspection circle, as specified in the AGMA standard. The single-pitch deviation in the standard provides no such line-of-action spacing measurement. For gears in which eccentricity is the dominant accuracy deviation, the value of the currently reported single-pitch deviation comes only from the magnitude of eccentricity and the total number of teeth in the gear. To receive the benefit of single-pitch deviation

measurements, the measurement must be moved from the tolerance circle to the base tangent direction. This may be done by a change in the measurement procedure itself or by the use of software which takes the eccentricity information found from the cumulative pitch data and makes the required translation.

It is possible that any influence of eccentricity deviation may be accompanied by other, more local geometry accuracy deviations, such as an out-of-round condition. This would certainly influence the pitch deviation data. At first thought, it may be considered that extracting the once-per-gear rotation sine curve data would simply reveal any out-of-round condition. However, the out–of-round influence may be accompanied by a local pressure angle deviation condition—enough to distort the cumulative pitch deviation data and so distort the results of such an attempt at further tooth shape analysis. Additional research on this subject may be needed to find a superior method for showing, and measuring, any out-of-round condition.

Not included in the gear accuracy set of measurements, but often supplied by elemental gear inspection software, is a set of tooth thickness data calculated from the common index measurements of both sets of tooth flanks. Again, if eccentricity is the dominant accuracy deviation, these tooth thickness values, one for each tooth, will follow their own sine wave shape. Averaging this data is considered a useful measurement of tooth thickness along an equivalent gear tooth ring circle diameter. As long as there are no other "local" tooth accuracy deviations, the averaging process may be considered valid. If there are such local deviations, averaging will obscure any data revealing their presence—a case of "throwing out the baby with the bath water."

Profile, total, slope, and form. All these measurements are made in the profile inspection process. Three or four teeth are selected, with their tooth number intervals being equal, or nearly equal. At each of the teeth, the gear is slowly rotated about its datum axis while the probe contacting the tooth flank moves in a base tangent direction, starting near the tooth fillet and proceeding to the tip round or chamfer (Fig. 4).

If the base circle of the ring of gear teeth is ideally centered at this datum axis, and if the shape of the tooth flank is an involute curve generated from this base circle, the shape of the measurement plots will be straight lines parallel to the plotted horizontal axis. If the other conditions are met, but the generating base circle differs in diameter from that specified for the gear, the plots will still be straight lines, but at some other consistent slope.

However, if the datum axis is displaced from that of the generating base circle, i.e.—when eccentricity is a dominant accuracy deviation—the plots will no longer be straight lines, but rather small portions of sine curves, with each portion starting along the sine curve according to a phase relation defined by the tooth's position around the circle of gear teeth (Fig. 5). If extended, the amplitude of the sine curve will be determined by the eccentricity as defined by the equations in Reference 6. Also, the extent of each portion of sine wave will be defined by the roll angle interval along the tooth profile examined during the profile measurement. If the gear has more teeth, this roll angle interval is likely to be small and each trace will consist of a smaller portion of a full (360°) sine wave.

When confronted by such a set of profile traces, with its variation from tooth to tooth of crown and hollow and variation of profile slope, and without appropriate training, it would be difficult for the observer to make sense of these profile traces. Not recognizing the role of eccentricity would leave the observer searching unsuccessfully for a manufacturing process which could produce such profile deviations. The AGMA standards would be improved by supplying the needed training.

Clause 7.6 (Ref. 1), and repeated here in Figure 6, shows such traces caused by eccentricity, not as sinusoidal curves with their apparent crowns and hollows but, misleadingly, as straight lines of distributed, varying slopes. There is also no reference relating these varying slopes to the degree of eccentricity.

The AGMA standards define methods of quantitatively evaluating measurement traces in three different ways (Ref. 2):

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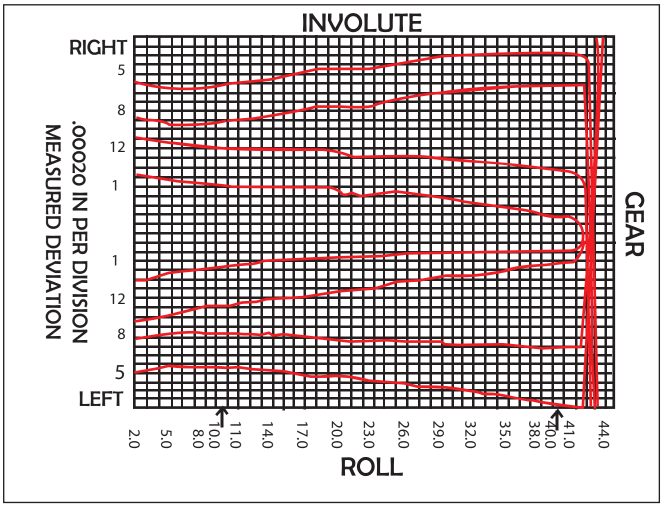

Figure 5—Profile measurement traces for gear with eccentricity.

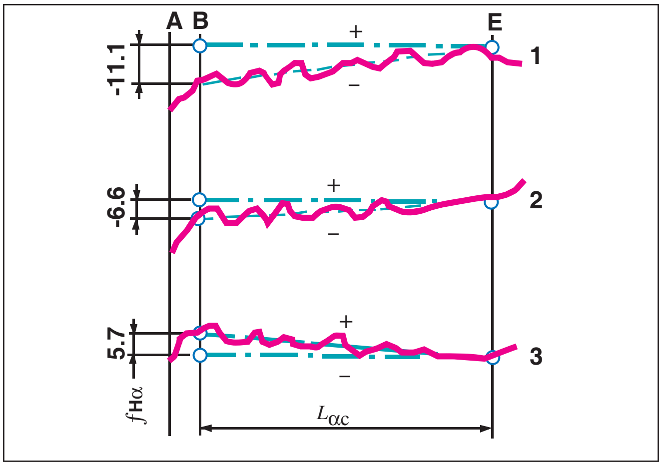

Figure 6—Profile traces as represented in AGMA 9151.

1) Total profile deviation is the full range of the profile curve or, if the profile has been modified by design, the full range between limit lines defined by the profile design modification.

2) Profile form deviation is the range of the profile curve as defined by limit lines matched to the mean profile line, curved if necessary.

3) Profile slope deviation is the range of the profile curve as defined by limit lines located where the mean profile line intersects the beginning and end of the active profile curve, with this mean profile line adapted to any design modifications.

Such evaluations make no attempt at explaining the possible role of eccentricity in the various measurement traces. Nor do they explain how the traces might change if the role of eccentricity was removed. They simply give quantitative values to be used in establishing the quality classification of the gears producing such traces.

Although not specified as having a role in defining gear accuracy, Reference 1 suggests averaging the data from all the (three or four) profile traces for each flank as a means of removing the effect of eccentricity and providing a clearer indication of the effective profile deviation. This suggestion creates two issues:

1) The reader is guided to two different methods for evaluating the quality of the gear—one by following the individual traces as the basis for accepting or rejecting the gear, the method of commercial significance; or, two, by examining the averaged data as a truer indication of gear quality.

2) While the averaging process can produce a valid result as long as all teeth are subject to the same quality influences, with eccentricity, for example, meeting this requirement as would a consistent profile slope deviation. However, if there are local differences in quality influences as, for example, in out-of-round gears, the averaging would likely obscure critical profile information. Cautions in using averaging where not appropriate are not included in the standard.

The most direct way of dealing with the complicating effects of eccentricity on profile measurements is, probably, by adding a separate set of profile trace plots. This second set would simply show the profile traces with the effects of eccentricity removed. The current set of data, actually composite measurements, would be transformed into two true, elemental measurements—eccentricity and true tooth profile traces. Such profile traces could then be further analyzed into their own set of elemental tooth accuracy deviations, such as pressure angle, crown and hollow, waviness and others. The process of enhanced profile analysis could be accomplished by added software features or by remeasuring the tooth profiles with a changed "datum" reference.

Helix: total, slope, form. These measurements are made in the lead inspection process. Three or four teeth are selected, with their tooth number intervals being equal, or nearly equal. For spur gears at each of the teeth, taking one set of flanks at a time, the gear is fixed against rotation while the measuring probe travels axially. For helical gears, the gear is slowly rotated while the measuring probe travels axially at a relative rate according to its specified helix angle (at the measurement diameter) or corresponding value of lead (Fig. 7). The probe readings may show end-effects, such as end chamfers, but these readings are normally excluded from measurement data analysis.

The AGMA standard, as part of its Gear Accuracy Classification System, evaluates the resulting lead traces into total, slope and form helix values by methods similar to those specified for involute traces (Ref. 1).

Eccentricity plays no significant role in helix measurements for spur gears. The traces may show the effects of crown and hollow, slope patterns and other such accuracy deviations. The slope patterns can be further analyzed into other elemental deviations such as taper or axial run out. This further analysis is not specified in AGMA standards, nor are tolerances assigned to them.

For helical gears, however, eccentricity does play a role in the lead traces produced. Aside from the kinds of accuracy deviations described for spur gears, eccentricity—without the introduction of corrections—will show curves corresponding to segments of sine waves (Fig. 8). The phase shift of individual segments will be determined by the interval of tooth numbers. If fully extended, the resulting sine curves will show amplitudes based on the eccentricity and the helix angle. The length of each sine curve will derive from the relationship of the gear's inspection face width to the gear's lead, as determined from its design specifications. If the face width, for example, equals the gear lead, the sine curves will extend for a full cycle of 360°. The treatment in the AGMA standard (Ref. 1) of the influence of eccentricity on helical gear measurement traces is as limited as it is for tooth profile measurement traces. Figure 9 shows a similar, simplified version of the resulting traces. What is also lacking for helical traces is a set derived with the effect of eccentricity removed. This would reveal the true nature of the remaining helix deviations, including those that readily appear for spur gear traces in which eccentricity plays no role.

Hidden run out. This type of accuracy deviation results from some form of a two-step manufacturing process. In the first step, the ring of gear teeth is manufactured by any process that leaves it eccentric to the datum axis. In the second step, the tooth flanks are reworked while maintaining the original, angular positions of the tooth spaces and keeping constant the new space widths along the datum pitch circle. An example of this second step process is a gear shaving process in which the shaving cutter takes on angular positions that largely follow the original tooth spaces. These tooth spaces positions have now become eccentric relative to the datum axis. Other examples may be found in certain roll forming processes, one of which is "tooth surface densification" of P/M gears in a set-up that centers the reworked gear on its datum axis.

Hidden run out is discussed briefly in Reference 3 and described in detail in Reference 7. It deserves special mention here because its presence is not readily revealed, or evaluated, in the standard "elemental" inspection processes. In the pitch deviation measurements, it appears simply as an eccentric gear, with only a hint of its special character. This hint appears in its unique phase relationship between the sine waves generated for the two flanks.

Another method of identification can be found through a special set of additional calculations using data from the cumulative pitch deviation measurements. As noted above, tooth thickness values are often calculated from this data. For the simple presence of eccentricity, these will vary as if they were points on a sine wave. This will also appear with hidden run out. However, if a second set of calculations is made of the space widths, the hidden run out is revealed, since these space width results will now be essentially constant around the gear.

The effect of hidden run out on gear performance is better revealed if the pitch measurements are made along the line of action, as recommended earlier. It is these pitch measurements, whether for simple eccentricity or hidden run out, that should be used to define gear accuracy. To determine the manufacturing process which requires correction, simple eccentricity or hidden run out, further analysis of the two sets of measurements may be needed.

Conclusion

It is proposed here that the benefits of elemental inspection would be extended by some limited additions or changes in the measurement processes and subsequent data analysis. Also important, these changes should include the presentation of results, whose content is currently determined by AGMA standards.

In summary, the changes are:

- Measure and report pitch deviations along a base tangent line, in place of along the inspection circle;
- Add plots of profile and lead measurements from which any effect of eccentricity has been removed;
- Treat the new measurements as true, elemental deviations without the role of eccentricity acting to produce composite deviations;
- Report eccentricity, amplitude and direction, as determined from the selected set of measurements, with the possible imposition of a tolerance.

These changes would increase the value of modern gear accuracy measuring equipment to those that have purchased them and continue to use them. They also open up the opportunity for the AGMA gear accuracy committee to lead the industry in their application. ◘

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Irving Laskin, *a consultant in gear technology specializing in fine-pitch gearing and a* Gear Technology *technical editor, received in 2008 the AGMA Lifetime Achievement Award for his long career in the gear industry. The award is given to a member of the industry who demonstrates vision and leadership, sharing knowledge and experience for the advancement of the gear community. Laskin has been involved in AGMA's technical committees for more than 25 years, serving as chairman of the Fine Pitch Gearing, Plastics Gearing and Powder Metallurgy Gearing Committees; Laskin was also a member of AGMA's Technical Division Executive Committee. He played a pivotal role in establishing the plastics and powder metallurgy segments of the industry within AGMA, and he has been instrumental in recruiting many companies to become members.*

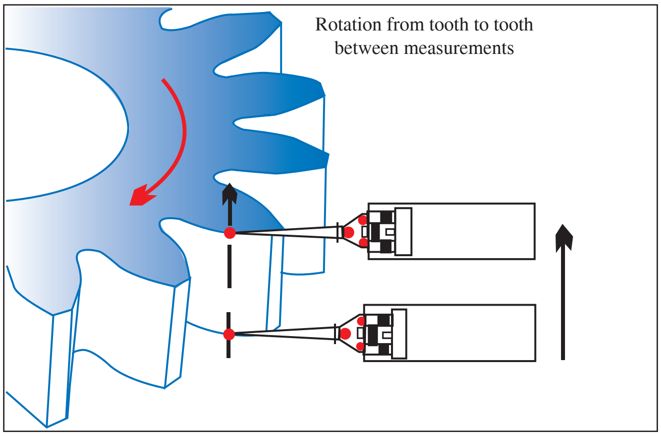

Figure 7—Measurement of helix (or lead) deviations.

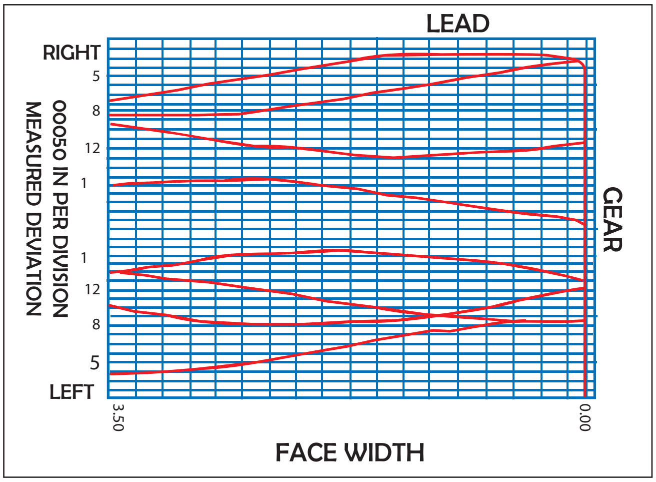

Figure 8—Helix measurement traces of gear with dominant eccentricity.

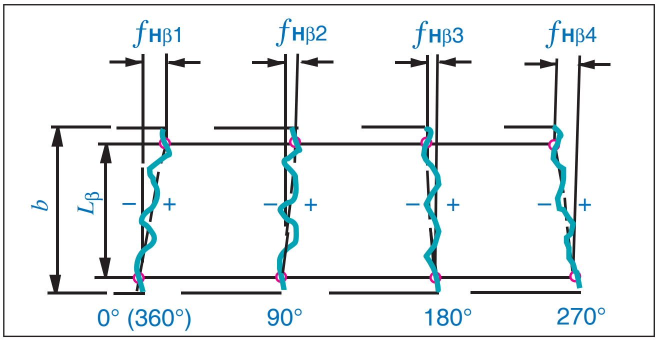

Figure 9—Helix traces for a helical gear as represented in AGMA 9151.