The Basics of Gear Metrology and Terminology Part II

Edward Lawson
Senior Applications Engineer, Mahr Corporation

In the last section, we discussed gear inspection; the types of errors found by single and double flank composite and analytical tests; involute geometry; the involute cam and the causes and symptoms of profile errors. In this section, we go into tooth alignment and line of contact issues including lead, helix angles, pitch, pitchline runout, testing and errors in pitch and alignment.

Tooth Alignment

Helical Lead and Helix Angles. The lengthwise profile of an involute helicoid gear tooth is a simple helical lead. Testing of this parameter is still commonly referred to as lead testing despite the changes in the AGMA standard, which now more precisely terms this parameter as tooth alignment. The helical lead of a gear tooth has the same geometry as the helical lead of a screw thread. It is defined by the axial advance (the lead) per 360 degrees of rotational displacement upon a cylinder. For spur gears, the lead is infinite (Fig 1).

While the typical screw thread embodies many complete helical leads, the typical gear tooth embodies only a fraction of one lead. It is, therefore, more difficult to visualize the helical geometry of the gear tooth. However, the helical gear tooth, which appears to be simply tilted at an angle to the gear axis is, in fact, both tilted and wrapped around a cylinder, thereby producing the helical geometry. If a gear tooth alignment is considered by unwrapping the pitch cylinder of the gear onto a flat surface, it will then truly appear as a straight line inclined at an angle to the gear axis. The helix/lead angles will be determined by the relationship of the diameter of the cylinder and the length of the lead specified for the tooth.

The helix angle is found between the tooth alignment and the gear axis while the lead angle is found between the tooth alignment and the transverse plane. It is common for these terms to be incorrectly used interchangeably. A close visual examination of a helical gear tooth will reveal that as the cylinder diameter increases, the helix angle also increases. It is important to note that this phenomenon is a function of differing diameters while the lead remains the same for all diameters of the gear tooth.

Testing Tooth Alignment. This characteristic of helical gear teeth allows for a simple tooth alignment test not unlike the generative tests described in Part I (*Gear Technology*, Sept./Oct.1998). In this case, a sensitive probe is brought into contact with the tooth at any diameter and is then carried in a direction parallel to the gear axis while the gear is rotated. The gear rotation must be in a direct relationship with the axial motion of the probe according to the lead of the gear. If the gear was to be rotated a complete 360 degrees, the probe would move axially a distance equal to the lead. If the tooth alignment being tested is perfect, the sensitive probe will measure no error.

Most such generative tooth alignment testing instruments use some sort of helix guide or sine bar arrangement. CNC devices test tooth alignment by controlling the movements of a rotary axis (spindle) and verticle slide that are not connected by any mechanical components. They are each caused to move under computer control in the same fashion as the classic mechanical instrument

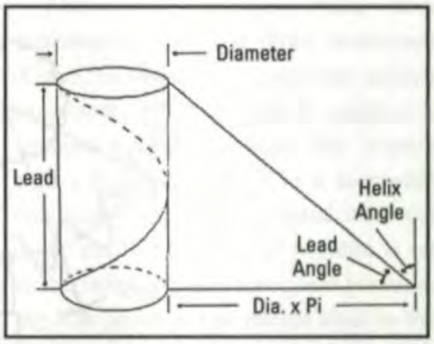

Fig. 1 — Tooth alignment (formerly "Lead"). Courtesy of AGMA.

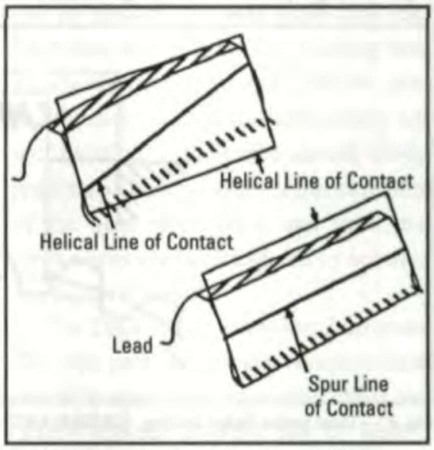

Fig. 2 — Line of contact. Courtesy of AGMA.

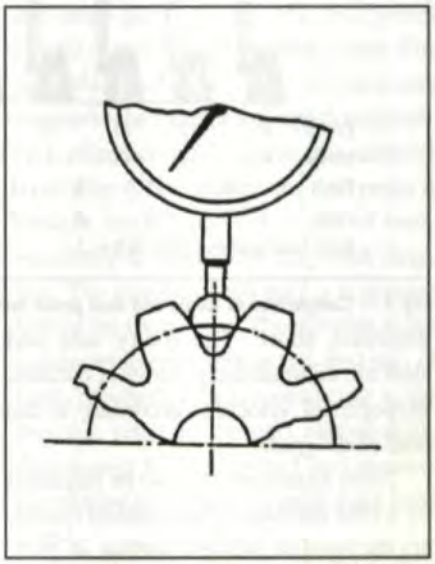

Fig. 3 — Pitchline Runout. Courtesy of AGMA.

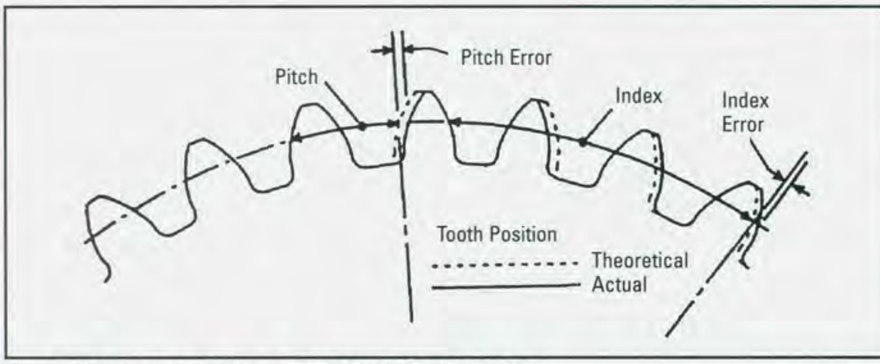

Fig. 4 — Pitch error and index error. ©AGMA/ANSI 2000-A88.

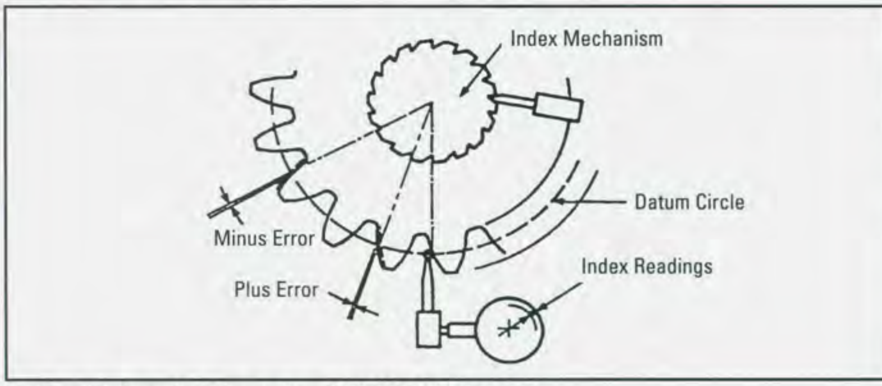

Fig. 5 — Single probe index testing. ©AGMA/ANSI 2000-A88.

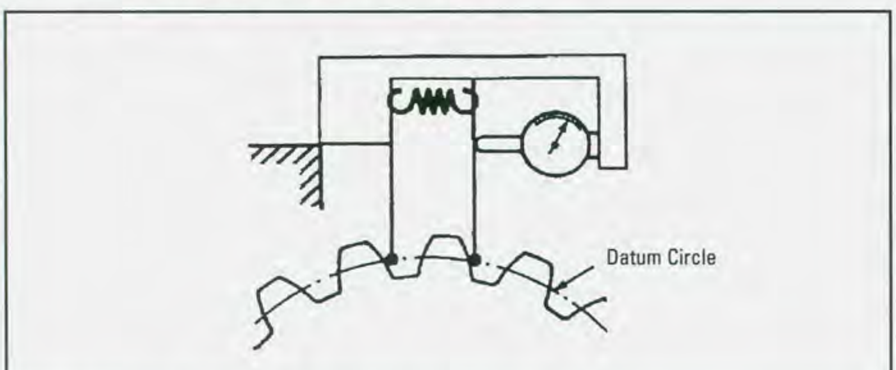

Fig. 6 — Dual probe index testing. ©AGMA/ANSI 2000-A88.

Probe	0		+2		+1		-1		-2		-4		-1		+1		0
Index	0		+2		+1		-1		-2		-4		-1		+1		0
Pitch		+2		-1		-2		-1		-2		+3		+2		-1	
Dual		0		-3		-4		-3		4		+1		0		-3	

Dual Total and Average-16/8 = -2

Fig. 7 — Comparison of single and dual probe test measurements. ©AGMA/ANSI 2000-A88.

described above. The rotary axis and slide are commanded to move at constant proportional velocities according to the lead of the gear.

Tooth alignment can also be inspected by CMM machines. This method considers the involute helicoid surface in rectilinear coordinates, a considerably more complex process than the classic generative method described above and an uncommon one.

Types of Tooth Alignment Errors. The primary concern associated with tooth alignment errors is their adverse effect upon gear strength and durability. Tooth strength ratings are normally calculated assuming that the torque load will be applied uniformly across the full face width of the gear. Tooth alignment errors can reduce the region of contact between mates, significantly increasing both the structural stresses and surface contact stresses on the tooth, reducing the gear's actual strength and durability values.

A common category of tooth alignment error is slope error. This type of error causes increased loading on the tooth ends, the place they are least capable of carrying increased stress.

Tooth alignment errors are not commonly associated with noise problems. A gear can have a substantial tooth alignment error and still produce excellent conjugate action if the involute geometry in the reduced region of mesh is of good quality. Tooth alignment errors can, however, increase noise levels for a given transmission error signature by increasing the loading on the gear teeth during meshing action.

Causes of Tooth Alignment Errors. Machine tool alignment problems produce tooth alignment errors that are consistent when one observes teeth located at various positions around the gear. Such tool alignment errors made in a direction perpendicular to tool feed produce tooth alignment errors of equivalent direction and slope on opposite tooth flanks. Errors parallel to the tool feed direction produce tooth alignment errors of different direction and slope on opposite tooth flanks.

Errors in gear blank accuracy or mounting produce tooth alignment errors that vary when one observes teeth located at different positions around the gear. One category of accuracy or mounting error is simple eccentricity wherein the axis of the gear feature is parallel with, but offset from, the axis of rotation. The other category of accuracy or mounting error is axial runout (a.k.a. wobble or cranking) wherein the axis of the gear feature is not parallel with the axis of rotation.

Both categories of accuracy or mounting error cause tooth alignment errors varying in slope in a sinusoidal pattern around the gear. However, only axial runout will adversely affect the performance of the gear. Simple eccentricity produces only apparent tooth alignment errors (as was the case with involute profiles). It is usually visible only in cases of high helix angles and large face widths. Simple eccentricity has no measurable effects upon the accuracy of spur gear tooth alignment. Segregation of the two categories of accuracy or mounting error is moderately complex and is not commonly done.

Line of Contact

As mentioned in Part I, gear teeth only contact one another within the plane tangent to their base cylinders. An interesting feature of the involute helicoid is that its intersection with the plane of action is always a straight line, so involute helicoid gear teeth are always contacting one another along straight line elements within their surfaces called lines of contact.

A line of contact for a spur gear is the same as a tooth alignment line. For helical gears, the line of contact is inclined across the tooth face at an angle (Fig. 2). It is thereby affected by both errors of involute profile and tooth alignment, which may combine in either a cumulative or compensatory fashion.

Observation of line of contact traces may permit acceptance of a gear with significant errors which are compensatory in nature. It is important in such cases to recall that the process is not operating properly even though the product is OK to ship. As a composite of the involute profile and tooth alignment parameters, the line of contact usually does not correlate well with process variables.

The line of contact is always inclined to the helix angle at the base circle of the gear. It is possible to test the line of action by moving a sensitive probe within the plane of action at the base helix angle while in contact with the tooth flank. Mechanical testers have been developed to do this test. CNC testers can also be programmed to make this test move. Line of contact testing is not common and AGMA standards do not tolerance it.

Pitchline Runout

Pitchline runout testing is an old and simple method of limited value. The test gear is mounted on a spindle free to rotate. A sensitive probe is brought into orientation to measure in a radial direction. A ball or other shape is selected to make contact with both flanks of the gear near the pitchline or other reference diameter. The probe is then moved into the tooth space until it reads zero while contacting both flanks and that position is set to be repeated on subsequent tooth spaces. The probe is then moved clear so the gear can be rotated, then moved back into the next tooth space. This process continues until measurements are taken on all the tooth spaces of the gear. The assumption is that a gear with no radial runout will produce all zero readings on the probe (Fig. 3).

Since this test is a double flank radial direction test, it relates only indirectly to gear performance. Pitchline runout test data can reveal radial eccentricity or out-of-round errors which produce gear transmission error. Certain manufacturing processes (e.g., shaving) often produce gears with significant angular errors that cannot be detected by double flank testing.

Pitchline runout errors typically result from gear blank geometry problems or gear blank mounting errors. These mistakes cause cyclic angular tooth position errors comparable to tooth index errors with respect to both duration and amplitude, variation of backlash (which becomes a major consideration in applications where minimum backlash is required), and apparent profile slope variation (which has little effect on gear performance).

Pitch and Index

Index Error. This is the displacement of any tooth on a gear relative to any other tooth, measured in a tangential direction. Index errors are commonly called cumulative pitch errors. This parameter is ideal for observing tooth position errors of longer duration such as eccentricity (one cycle per revolution) or out-of-round (Fig. 4).

Pitch Error. This is the displacement of any tooth on a gear relative to an adjacent tooth, measured in a tangential direction. Commonly called adjacent pitch error, this parameter is ideal for observing tooth position errors of shorter duration associated with localized meshing conditions. Less commonly used is the spacing error parameter—the difference between the pitch value for one pair of teeth and the pitch value for the adjacent pair of teeth.

Pitch Testing. Testing tooth location parameters is done with two types of instruments: the single probe and the dual probe. The single probe is usually seen as providing more reliable information, especially in the presence of larger numbers of teeth. However, the dual probe may be superior for very large diameter gears.

The Single Probe Pitch Test Instrument. The single probe instrument (Fig. 5) compares tooth positions against an accurate dividing head. In practice, a sensitive probe is brought into contact with a tooth, measuring in a tangential direction. The gear is rotated until the probe reads zero, and that position is set as the reference for subsequent positioning. The probe is then moved clear so the gear can rotate to the next tooth position. The probe is then brought back into contact to measure the next tooth until each tooth has been tested. The dividing head accurately rotates the gear 360°/N, placing the next tooth at its theoretically correct location so the probe should always read zero. This provides a direct reading of the gear index error, and from that, pitch errors can be calculated by subtracting adjacent values.

The Dual Probe Pitch Test Instrument. The dual probe instrument compares tooth positions against the pitch of an initial, randomly selected adjacent pair of teeth. It measures the differences between that pair and other pairs of teeth. The two probes consist of a fixed and movable probe. The moveable probe measures displacement relative to the fixed probe, which establishes a reference point against the adjacent tooth (Fig. 6). In practice, the dual probe is brought into contact with a pair of teeth, measuring in a generally tangential direction. The gear is rotated until it is stopped against the fixed probe. The movable probe is then set to read zero on this first pair of teeth. The dual probe is moved clear so the gear can rotate to the next pair of teeth, then moved back to contact and measure the relative pitch until all teeth have been tested.

To calculate pitch errors from dual probe data, it is first necessary to find the average value for all the relative pitch measurements. All measurements would be equal to that average value if the gear were perfect. Subtracting the average from measured values gives the pitch errors for the gear. Successive summation of those pitch error values produces the index error values for the gear. It is a common misconception that the dual probe test instrument will directly measure pitch errors. It is important to understand that the average value must be subtracted before pitch error values are produced.

Figure 7 displays the various tooth location parameters. It shows an eight-tooth gear which has been unwrapped into a straight line. A sensitive probe is brought into contact with the first tooth and zeroed. It is then moved to the theoretically correct position on each subsequent tooth and the tooth position is measured as shown in the first line of data. This data shows that tooth #2 is 2 increments out of position to the right (+2), and that tooth #5 is 2 increments out of position to the left (-2). Notice that the index errors relative to tooth #1 are measured directly by this procedure, which is the equivalent to a single probe test. The worst index error (total error) is 6 increments and occurs between tooth #2 (measured +2) and tooth #6 (measured -4). The index error is not given a + or - sign since that would depend upon the direction taken around the gear from #2 to #6.

Pitch error data can be derived from the index data by successive subtraction. For example, the +2 pitch error of tooth pair 7 and 8 is found by subtracting the #7 value (-1) from the #8 value (+1). The error is + since the teeth are too far apart rather than too close together. A possible set of dual probe values for this gear is also provided. The average is found to be -2. Subtraction of that average value from the actual measurements will produce the same pitch values as the single probe approach. Successive summation of pitch values will produce index values. The +1 index value for #8 equals the #7 index value (-1) plus the pair 7 and 8 pitch value (+2).

The Causes of Pitch and Index Errors. Pitch and index errors are both caused by three things: problems with machine tools, cutting tool problems and gear blank and mounting errors.

Kinematic errors in machine tools, including simple looseness, can generate pitch errors when used with certain design processes that transfer the imperfections of the cutting tool directly to the work piece such as hobbing a gear with a multiple thread hob where the number of hob threads is a factor of the number of teeth on the gear. That process will result in the thread spacing errors of the hob transferring directly to pitch errors on the gear. Index errors may be associated with processes that do not control the angular positioning of the gear during cutting (e.g., shaving), but another possible cause is runout in a change gear, causing the production gear to accelerate/decelerate its rotation during cutting.

Gear blank and mounting errors include both eccentricity and out-of-round problems and are the primary cause of index errors. A gear that is otherwise perfect except for being eccentric by .005 mm will display a sinusoidal pitchline runout of .010 mm. This will result in an acceleration/deceleration of the points of contact with the mating gear teeth along the line of action of .010 mm. Eccentricity in the gear blank can produce pitch errors in an apparant sinusoidal pattern that is especially noticeable when the number of teeth is relatively small. However, this apparent pitch error will not adversely affect gear meshing action performance. As with the involute profile and helical tooth alignment, if a proper observation of simple eccentricity is applied to the pitch data in an appropriate fashion, the resulting modified pitch error data is valid for observations of localized tooth meshing conjugacy.

Problems Arising From Pitch and Index Errors. Pitch errors lead to gear noise by being a significant source of transmission error. However, the noise produced by a pitch error is typically less objectionable than the equivalent noise produced by profile errors. This is because some tooth pairs show plus pitch errors and others minus errors, causing a less consistent transmission error characteristic than profile type errors. Index errors are not often associated with gear noise trouble, though the cyclic modulation they can produce may be noticeable. It is also possible for the increased loading of a planetary set caused by index errors to cause increased noise levels. Index errors are also a common cause of ghost harmonics, an error which may appear in index test data if they occur at lower than mesh frequencies.

Both pitch and index errors lead to strength problems since dynamic loading promotes fatigue. The shock load that occurs when mispositioned teeth enter mesh adversely affects the strength of those teeth because the dynamic stresses involved will be higher than the tooth was designed to take. Localized pitting and other durability problems can also occur in the region of initial contact between mispositioned mating teeth.

Other strength and durability problems associated with index errors include increases in dynamic loading in high-power, high-speed gear drives due to cyclic changes in rotational velocity and backlash variation if the problem is caused by pitchline runout. Index errors also significantly reduce load sharing in planetary gear sets, increasing the importance of single flank testing, either composite or analytical, on gears produced for automotive style automatic transmissions as those are often finished by shaving.

Finally, index errors can degrade the performance of gears that must maintain timing relationships. This includes positioning applications such as robots and media movement applications such as printing presses. ○

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