The Basics of Gear Metrology and Terminology Part I

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It is very common for those working in the gear manufacturing industry to have only a limited understanding of the fundamental principals of involute helicoid gear metrology, the tendency being to leave the topic to specialists in the gear lab. It is well known that quiet, reliable gears can only be made using the information gleaned from proper gear metrology.

Part I: Gear Inspection

Gears are one of the most common devices within the world of engineering, offering an elegant solution to the problem of effective power transmission. Modern gear drive designs must provide quiet, reliable service at high power densities, which can only be achieved by using gears which accurately embody a geometry like the involute helicoid system. Gear metrology may be divided into two subtopics, functional gaging and analytical testing. These two categories of gear inspection provide fundamentally different types of information, each with its advantages and disadvantages. They can each be further divided into single flank and double flank testing procedures. It is important to understand the capabilities and limitations of these categories because misconceptions about the proper meaning and usage of the information they provide are very common.

The functional gaging type of gear inspection can be characterized as an "attribute inspection," meaning that it determines if a given production piece will function as intended in the product. It does not determine whether the various elemental specifications affecting functional performance are in tolerance or control since such elements often combine in either a cumulative or compensatory fashion. Functional gaging is, therefore, more qualitative than quantitative. More sophisticated versions of gear functional gaging instruments can provide an assortment of numerical test data. However, since most of this information is based upon a fundamentally composite observation, it is usually best applied to process performance rating exercises rather than to control of process variables as these relate more directly to elemental test parameter data.

Functional gaging observations can be based upon either single flank or double flank meshing configurations of the master and production gears. The single flank version provides a direct observation of transmission errors, while the double flank version provides observation of variation of center distance.

The analytical testing type of gear inspection would be characterized as a "variable inspection," meaning that it provides numerical information pertaining to given elemental parameter specifications of a production piece. This type of test data often serves as the basis for accept/reject decisions. However, since analytical testing is unavoidably based on sample type data (the number of teeth tested, number of test traces per tooth), it could fail to detect anomalous errors such as nicks or hard spots. Composite action testing, which includes observation of all surfaces of all teeth, would be a more reliable method for detecting such errors which, though not systematic, could adversely affect product performance.

Analytical testing is generally quantitative rather than qualitative and is usually the most valuable source of process control information since process variables usually relate more directly to elemental parameters. Like functional testing, analytical testing observations can be based upon either single flank or double flank inspection practices. AGMA tolerances are provided for involute profile, tooth alignment (formerly called lead), pitch and pitchline runout parameters. All are single flank parameters except pitchline runout.

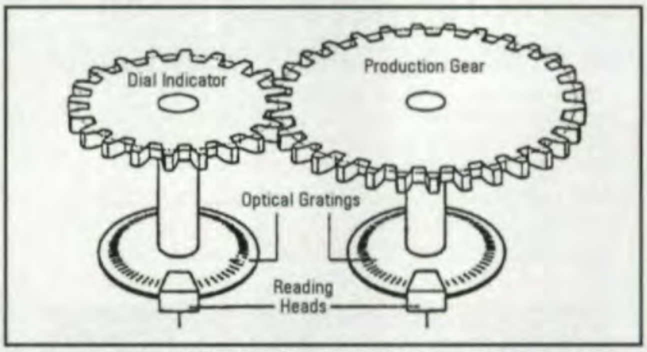

Fig. 1 — Functional Gaging: Single Flank Composite. © ANSI/AGMA 2000-A88.

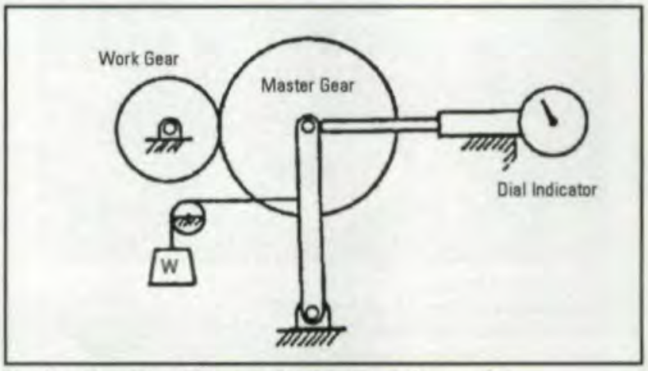

Fig. 2 — Functional Gaging: Double Flank Composite. © ANSI/AGMA 2000-A88.

Single Flank vs. Double Flank

Single flank testing provides observations (analytical or functional) of gear geometric quality involving only one flank at a time. The data provided is tangential rather than radial in direction, thereby offering information about the way the gear operates—an advantage over double flank testing operations. A single flank composite testing instrument (see Fig. 1) provides two spindles, to carry the master and production gears, mounted in fixed locations on the instrument to simulate the mounting of the gears at their proper center distance with backlash. Each spindle is fitted with a high-precision angular encoder as well as a means to apply a braking load to one of the gears as they are rotated through mesh, thereby maintaining contact on the loaded flank. The gears are placed on the spindles, brought into single flank contact with backlash and rotated through at least one revolution of the production gear. During that rotation, variation in the relative rotational velocities of the gears is observed. This procedure is based upon the assumption that two perfect gears would produce zero variation in rotational velocity, or no transmission error.

Double flank testing provides observations (analytical or functional) of gear geometric quality involving both flanks simultaneously. It provides radial rather than tangential data, information related only indirectly to the way the gear operates. The double flank composite testing instrument (Fig. 2) provides two spindles to carry the master and production gears. One of the spindles is mounted in a fixed location on the instrument and the other is mounted on a linear slide which is arranged to permit the center distance between the two gears to vary. A means is also provided to apply a load to the slide mechanism which will serve to maintain zero backlash between the gears. In operation, the gears are mounted on the spindles, brought into zero backlash mesh and rotated through at least one revolution of the production gear. During that rotation, variation in center distance between the gears is observed. This procedure assumes that two perfect gears thus tested would produce zero variation in center distance.

Double flank composite action test data can reveal radial eccentricity or out-of-round errors that can produce gear transmission error. It cannot, however, reveal angular tooth position errors which also produce transmission errors. Certain manufacturing processes (i.e. shaving) often produce gears with significant angular errors that cannot be detected by double flank testing. It is also not possible with this testing method to directly relate large tooth-to-tooth errors to gear function, including noise problems. It can, however, find non-systematic errors such as nicks, burrs or hard spots and it does offer an ideal means for evaluating functional tooth thickness based upon observations of the average center distance during testing with a calibrated master gear. Occasionally, one of the spindles is fitted with a gimble mounting to permit tilting in response to line of contact errors in the production gear. For spur gears this observation relates very well with tooth alignment errors. However, for helical gears the observation is equally and inseparably affected by both lead and profile errors.

Errors Detected by Composite Action Testing

If the error observed during either a single flank composite action test, or a double flank composite action test is plotted, the resulting trace will typically consist of long term and short term error components.

The long term component is composed of two categories of error, the most common occuring in a sinusoidal pattern once per revolution of the production gear and relating to the eccentricity of its pitchline. The second category relates to errors of the gear's shape or roundness. For example, a thin-walled ring gear which has been held in a three-jaw chuck with excessive force could display a long term error of three cycles per revolution.

The short term component is normally observed at a frequency of one cycle per mesh cycle. In a single flank test, this type of error relates to errors of tooth geometry and is directly related to noise problems, which may only be inferred from double flank tests. Frequency spectrum analysis of single flank test data usually correlates very well with the noise patterns generated by problem gears. Also, because short term errors occuring in regions of substantial slope on the long term component are affected accordingly, some standards permit the removal of the long term component from the test data before observations of the short term component proceed.

Occasionally, another pattern of short term error is observed in the single flank composite action test which does not correlate with the meshing cycle frequency. Commonly referred to as ghost harmonics, these patterns typically relate to kinematic errors in the associated machining operations.

Testing Machines

The classic method of testing an involute is to employ a base circle disk made to the same diameter as the base circle of the gear to be tested. That disk is mounted on a spindle which can also carry the gear. The device must also provide a linear slide arranged so as to operate in a direction tangential to the base circle disk. The slide carries a straight edge which is held in firm contact with the disk. A sensitive measurement probe is also carried by the slide. The probe is placed so that it will contact one of the gear teeth within the plane of action.

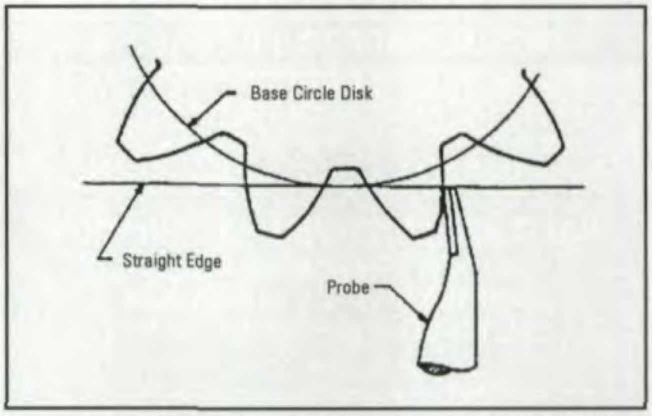

Fig. 3 — Involute Profile Testing Probe. © ANSI/AGMA 2000-A88.

The device is moved through a course of motion which will cause the probe to traverse the gear profile from root to tip following an involute path (Fig. 3). Because of the arrangement of the inspection device, rotating the gear with the disk and carrying the probe with the straight edge, this is automatic. As the disk and straight edge roll past one another, the straight edge and probe travel a linear distance equal to the circumferential distance upon the base circle disk associated with the angle through which the disk and gear have been rotated. During this motion, the probe is carried along within the plane of action by the straight edge. If the cam (the involute gear tooth) is an accurate involute, the sensitive probe will measure no error during the motion.

There are several different kinds of test machines. The involute test instrument uses the method described above. The straight edge mounted on the slide rolls tangentially with the disk mounted on the spindle. The probe is carried within the plane of action while contacting the gear tooth that is carried along with the disk. A related device uses a master involute cam on the spindle instead of the base circle disk. This cam drives a follower on the slide which carries the probe. The gear tooth's involute profile can also be inspected using a coordinate measurement machine (CMM). This method considers the involute helicoid surface in rectilinear coordinates, a considerably more complex procedure than the classic generative methods described above and not very common.

The most common category of involute test instrument today is the CNC tester. These devices employ a rotary axis and linear slides that are not kinematically connected to one another. Instead, each axis is fitted with a high resolution scale so that its movements can be controlled by a CNC module. Typically, an axis radial to the rotary axis positions the measurement probe to contact the involute tooth flank within the plane of action. The rotary axis and tangential linear slide are then commanded to move at constant velocities such that the linear distance travelled by the slide is equal to the circumferential distance upon the theoretical base circle of the gear associated with the angle through which the rotary axis travels.

Another type of CNC tester uses the computer controlled axes in a fundamentally different way to inspect the involute. Such instruments move the measurement probe in a radial direction only, while the rotary axis is moved in a nonlinear relationship according to the given involute. This practice lowers the cost of the instruments due to the lack of the tangential measurement axis normally used to generate the involute according to the constant rise cam principal.

Part II: The Involute Profile

An ideal gear would provide both the smooth running properties of friction disks and the positive power transmitting qualities of teeth. This can be accomplished by using teeth with a geometry which conforms to the law of gearing: "In order for two gears to transmit uniform rotary motion, the common normal of the mating profiles must pass through the same point on their line of centers at every point of contact." Such gears exhibit conjugate action, which is to

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say they exhibit progressive contact between mating teeth while their pitch circles rotate together at uniform, proportionate velocities.

There are limitless geometries which will satisfy the law of gearing, but no geometry accomplishes this task with the elegant simplicity of the involute helicoid system. Since it meshes with a straight sided theoretical rack, it can be accurately manufactured with relatively simple, straight-sided cutting tools. The involute helicoid geometry also has the property of operating on varied center distances without affecting its ability to provide uniform transmission of rotational motion at the same ratio. All other geometries are conjugate only at their design center distance.

Involute Geometry

An involute can be defined as the locus of a point on a line rolling on its base circle or, in three dimensions, a base cylinder. It can be imagined like this: envision a tin can as the base cylinder. Fasten a string to some point on the can and wrap it part way around while holding it taught. The string now represents a line or plane tangent to the base cylinder. This is the line (or plane) of action. Focus on a point where the string lies wrapped next to the can and begin to slowly raise the string away, keeping it taught all the time (Fig. 4). As it rises, the path followed by the point on the string as it moves up and away from the can will be an involute. At first, the point will move nearly straight up from the surface of the can. It will then quickly begin to follow a curved path similar to an Archimedes spiral. That path is the involute curve.

Two things are important to note here. The first is that this only occurs within the plane of rotation, perpendicular to the axis of the base cylinder. It is also important to note that, at any point you wish to consider along the involute curve, the string (line/plane of action) is perpendicular to the involute. Further, the curvature radius of the involute is always equal to the length of the string (line/plane of action) from the involute to the point of tangency of the string with the can (base circle/cylinder).

Consider now the same base circle (Fig. 5) with a single line of action tangent to it. In this case, the base circle can rotate about its axis when the line of action is pulled to the left. Two equally spaced points along the line of action have generated two parallel involutes as the line of action was pulled left. The distance between the involutes along the line of action is equal

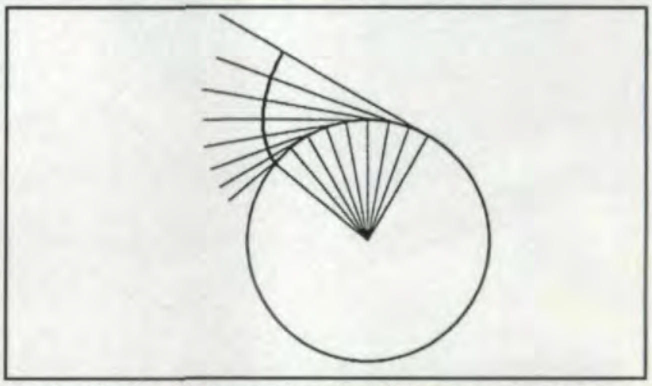

Fig. 4 — Circle with tangent lines describing an involute curve. Courtesy of AGMA.

to the distance along the circumference of the base circle. This is true because the same points on the line of action (string) that have generated these two involutes were once resting upon the surface of the base circle (can) before the involutes were generated by pulling away the string.

The Involute Cam

This observation gives rise to the most important property of the involute, that it will serve as a constant rise cam to a follower that is constrained to move within the plane tangent to the base cylinder of that involute. Imagine that such a follower has been positioned within the plane of action and in contact with the involute curve to the right. Now consider what will occur if the base circle is rotated counterclockwise through the angle required to move the involute at the right to the position of the involute at the left. The follower will be driven to a position within the plane of action contacting the left involute. It has been driven a distance along this line *equal to the length of the base circle circumference swept* by the counterclockwise rotation of the base circle. Any such rotation of the base circle and its involute "cams" will produce such a constant displacement of such a follower.

Figure 6 shows two base circles with a single line of action tangent to both. Involute profiles from both base circles interact with the string as we have seen before but now, with the two circles arranged to share this single line of contact, we can also see the two associated sets of involutes interacting. It can be seen that these involute profiles only contact one another within the plane of action. This condition also exists for all involute helicoid gear sets, where the mating tooth flanks only contact one another within the plane of action which is tangent to the base cylinders of both gears.

Observe the interaction of these mating constant rise involute cams. Begin with the point of contact labeled 2 near the base circle of the upper gear (driver) and at the OD of the lower gear (driven) in Figure 6. Now, rotate the driver counterclockwise through an angle necessary to move its involute to location 3. As this move proceeds from location 2 to 3, the point of contact with the mating involute is driven along the line of action, carrying the driven profile also to location 3. The distance travelled along the line of contact is equal to the circumferential distances along both base circles swept by their rotations which will be in proportion to their diameters.

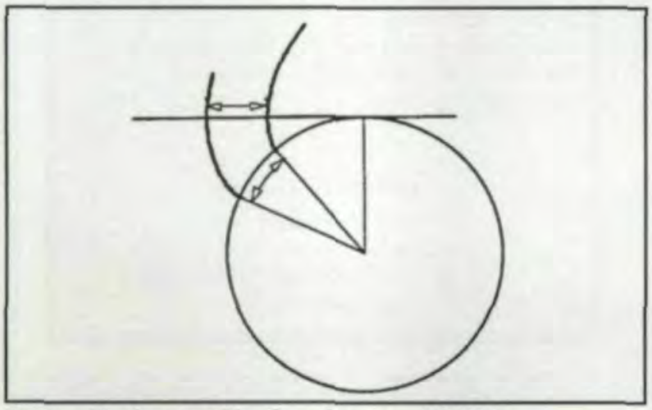

Fig. 5 — The Constant Rise Cam. Courtesy of AGMA.

Therefore, any rotation of the driver will cause an exactly proportionate rotation of the driven gear according to their diameter ratios.

Profile errors — Symptoms

Involute profile errors can result in gear noise, strength problems associated with dynamic loads promoting fatigue and durability problems associated with localized contact stress. Gear noise invariably relates to transmission error or inconsistent rotational velocities caused by geometry errors. Profile errors have a particularly troublesome effect upon

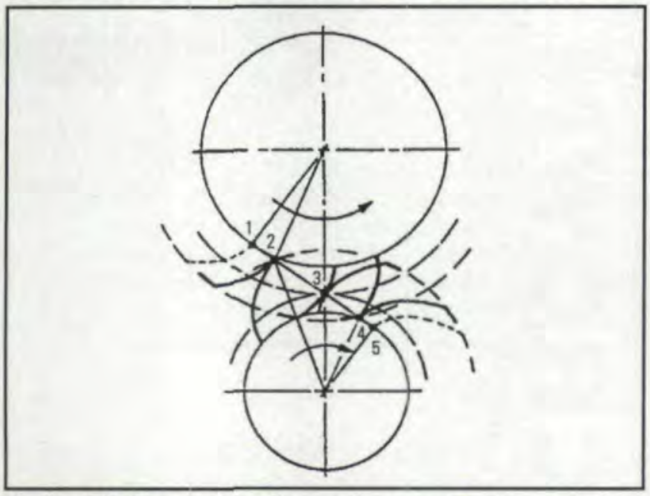

Fig. 7 — The Constant Rise Cam produces constant transmission of rotational motion. Courtesy of AGMA.

transmission error because they tend to be consistent in the teeth of the gear. This causes transmission errors at mesh frequency which is usually in the range of human audio acuity. Also, since the error is typically consistent for all teeth, the associated mesh frequency transmission error is usually of consistent amplitude throughout the rotation of the gear. This is perceived by the ear as a pure tone which is much more objectionable than a noise source of equal average amplitude that exhibits a modulated frequency of amplitude.

Involute profile errors can also adversely affect the strength and durability of a gear. Tooth strength ratings are calculated assuming that the torque load will be applied consistently and that loads applied at the critical region near the tooth tip will be shared by adjacent teeth entering mesh. Profile errors can increase dynamic loading and tip loading conditions thereby promoting fatigue and premature failure. Localized tooth contact stresses are also increased by profile errors that accelerate pitting and similar durability failures.

Profile errors—Causes

It is clear the primary contributors to involute profile errors are cutting tool accuracy and mounting errors. Cutting tool geometry errors typically transfer consistently to the gear profile on a one-to-one basis. Since other influences can also affect the gear profile, it is important that the cutting tools are significantly more accurate than the gears they are expected

to produce. Mounting errors can be even more problematic. A perfect cutting tool mounted inaccurately will perform no better than a low grade, inaccurate cutting tool. The use of bent or dirty tool arbors and failure to check truing diameters are possibly the most common and costly sins occurring in gear cutting operations. Errors in cutting tool accuracy or mounting tend to produce involute errors that are consistent when one observes teeth located at various positions around the gear. Errors in gear blank accuracy or mounting tend to produce involute errors that vary when one observes teeth located at various positions around the gear.

Gear blank accuracy and mounting errors are composed of two categories, eccentricity and out-of-round. Eccentricity conditions produce a sinusoidal pattern of variation in the slope trend of the involute test traces taken at various positions around the gear. Out-of-round conditions produce deformation of involute traces according to the given roundness error pattern. Radial runout of a gear caused by either an eccentric blank or an eccentric mounting of a good blank will cause a characteristic error pattern in which the profiles will display a slope error that varies in a sinusoidal pattern around the gear). This category of apparent profile error will not adversely affect the strength or durability of a gear or contribute to the generation of noise. Runout can be the source of several types of problems that affect gear performance. However, the sinusoidal pattern of profile slope errors it creates is not one of those problems.

It is possible to produce a gear with a substantial out-of-round condition that would exhibit proper conjugate action with a mate. Such gears are sometimes produced when a cyclic acceleration/deceleration is desired in a mechanism. However, when a gear that is intended to be round is deformed into an out-of-round condition during manufacturing, it cannot be expected to operate without an associated detrimental effect, as would be the case with simple eccentricity.

Recognizing the absence of detrimental effects from eccentricity-based apparent profile error, procedures have been employed that tolerance only averaged profile errors. This practice is inadequate because averaging may also remove the detrimental effects of out-of-round conditions. Rather, it is only correct to adjust test results according to the gear's simple eccentricity condition which has first been determined by analysis of its radial runout or by a more complex geometry-based analysis of the profile traces. Watch for the conclusion in the next issue of *Gear Technology*. ○

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