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Separation of Runout from Elemental Inspection Data

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TECHNICAL PAPER

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

As reported previously (AGMA 93FTM6), Runout due to eccentricity influences Index, Pitch and Profile inspection data for spur and helical gears and Tooth Alignment inspection data for helical gears. This paper reviews the numerical procedure currently used with Index and Pitch data to determine the magnitude and direction of the Runout and to replot the inspection data with the Runout influence removed. It also introduces a special numerical procedure to perform the same function with Profile and Tooth Alignment inspection data. This new numerical procedure is effective in the presence of such tooth geometry features as slope variation (e.g., pressure angle variation in Profile and helix angle variation in Tooth Alignment), non-linearity (e.g., tip relief in Profile and crown in Tooth Alignment), and waviness. The numerical procedure is demonstrated for Index, Pitch, and Profile inspection data taken from a test gear.

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Introduction.

In the manufacture of gears, one of the common variations from ideal gear geometry is the presence of Runout. In the broadest use of the term, Runout covers Axial Runout (wobble) and Radial Runout, with the latter as a combination of Eccentricity and Out-of-Roundness. Each of these variations detracts in its own way from ideal performance of the gear and each deserves to be studied. This paper, as did a previous paper [1] for which this is a continuation, deals with the Eccentricity component of Runout in spur and helical gears.

The previous paper showed quantitatively how this Runout, expressed by the magnitude and direction of eccentricity, influences the inspection results for the Elemental Variations of Profile, Index, Pitch, and Tooth Alignment (the last, on helical gears only). It was noted that any system of tolerances for such inspection results should consider the information in these relationships. This is especially true when the procedures for inspection data interpretation simply lump together the effect of eccentricity with all other sources of variations. The present AGMA interpretation procedures, as defined in AGMA 2000-A88, Gear Classification and Inspection Handbook, does just this, as, for example, in its use of K-charts for evaluating Profile and Tooth Alignment inspection data.

A better approach to analyzing such inspection data is to separate out the individual components of the total measurement and to judge the gear quality accordingly. This approach is partially applied in ISO standards for gear quality [2] which establish tolerances for individual components of an inspection record. However, the separation process described in these standards is incomplete and approximate. This may be a result of the limitations of traditional inspection equipment. The introduction and increasingly widespread use of computer controlled inspection machines, with their internal data processing capabilities, now make it possible to thoroughly and more accurately define procedures for separating the component variations. This paper describes such procedures for separating the Runout eccentricity component from Index (and similarly for Pitch), Profile, and certain cases of Tooth Alignment.

Runout Eccentricity and Gear Quality.

It should be pointed out that separating this Runout from other types of gear geometry variations is not merely an academic exercise, or even just a diagnostic tool. Inspection results are used to predict how well the gear will perform in its intended application. It is a waste to reject a manufactured gear for exceeding any of these elemental tolerances because of the unseparated contribution of eccentricity, when the eccentricity itself will not significantly affect performance.

It is similarly a waste to specify tighter quality classes, and the more expensive manufacturing processes they demand, because of a failure to distinguish the true critical quality features.

To judge the relative significance of the Runout eccentricity in evaluating gear performance, consider first that during gear operation, eccentricity by itself does not change basic tooth geometry. It simply continually moves the location of the true center of that geometry in a circular pattern. Consider next what the different Elemental variations are presumed to reveal about gear performance and whether this changing center location can affect these performance characteristics, as follows:

- Profile variations, in the form of excessive slope differences from the specified ideal, are understood to predict additional impact at load transfer and other undesirable dynamic load conditions during the tooth-meshing-cycle. These slope variations, by introducing a mis-match in base pitch between mating gears, can cause reduction in gear life or unacceptable vibration and noise at frequencies based, typically, on tooth meshing rates. However, consider a gear which is otherwise ideal but has some eccentricity which appears as apparently excessive Profile variation. Such a gear has no variation in true base pitch and will not suffer the same kind of tooth-meshing-cycle dynamic effects. There may be some dynamic influence from the eccentricity, but only at the much lower frequency based on rotation rate and, therefore, generally with a much lesser effect on gear life, vibration, or noise.

- Pitch variations (or differences in successive Index measurements) also suggest life-reducing impact during meshing tooth load transfers. Here again, the otherwise ideal gear, with enough eccentricity to show an apparently excessive maximum Pitch variation, will experience none of this presumed impact.

- Tooth Alignment variations suggest a departure from uniform tooth load distribution and a resulting reduction in gear life. In otherwise ideal helical gears, for which pure radial eccentricity can create an apparently excessive Tooth Alignment variation, the true base helix angle is unchanged and there is no loss in uniform tooth load distribution.

It is true that eccentricity has its own set of undesirable effects on gear performance, such as variation in backlash and angular position accuracy, which may be critical in some gear applications. The necessary response, therefore, is not to ignore eccentricity, but to identify its scale and avoid its possibly misleading influence on other features of gear geometry quality.

Axial Runout (Wobble)

The above comments on how some aspects of gear performance may be indifference to Radial Runout caused by eccentricity do not generally apply to Axial Runout. Axial Runout will adversely affect tooth load distribution and can introduce additional undesirable dynamic effects. Outside of some brief comments, this paper does not consider Axial Runout and how it might be revealed in Elemental inspection procedures. This important issue has been left to future study.

Effect of Runout Eccentricity on Inspection Measurements.

The previous paper [1] developed the following equations that relate the eccentricity to the Element variation measurements. The symbols and directional conventions used in these equations are shown in Figure 1 and Table 1.

Index measurements on the left and right flanks:

$$M_{xL} = \frac{e}{\cos \phi_{Mt}} \sin \{ [\theta_{eIm} + (\phi_{Mt} - \alpha_{pMt})] + \tau(k-1) \} \quad [\text{Eq 1}]$$

$$M_{xR} = \frac{e}{\cos \phi_{Mt}} \sin \{ [180^\circ + \theta_{eIm} - (\phi_{Mt} - \alpha_{pMt})] + \tau(k-1) \} \quad [\text{Eq 2}]$$

Pitch measurements on the left and right flanks:

$$M_{pL} = \frac{e}{\cos \phi_{Mt}} (2\pi/N) \sin \{ [90^\circ + \theta_{eIm} + (\phi_{Mt} - \alpha_{pMt})] + \tau(k-1) \} \quad [\text{Eq 3}]$$

$$M_{pR} = \frac{e}{\cos \phi_{Mt}} (2\pi/N) \sin \{ [-90^\circ + \theta_{eIm} - (\phi_{Mt} - \alpha_{pMt})] + \tau(k-1) \} \quad [\text{Eq 4}]$$

Profile measurements on the left and right flanks:

$$M_{\phi L} = e \sin \{ [(\theta_{eIM} - \alpha_{PBt})] + [\tau(k-1) + \epsilon_M] \} \quad [\text{Eq 5}]$$

$$M_{\phi R} = e \sin \{ [(-\theta_{eIM} - \alpha_{PBt})] + [-\tau(k-1) + \epsilon_M] \} \quad [\text{Eq 6}]$$

Tooth Alignment measurements on the left and right flanks (of helical gears):

$$M_{\psi L} = e(\cos \psi) \sin \{ [\theta_{eI} + (\phi_{Mt} - \alpha_{PMt})] + [\tau(k-1) + (360^\circ/L) \times M] \} \quad [\text{Eq 7}]$$

$$M_{\psi R} = e(\cos \psi) \sin \{ [180^\circ + \theta_{eI} - (\phi_{Mt} - \alpha_{PMt})] + [\tau(k-1) + (360^\circ/L) \times M] \} \quad [\text{Eq 8}]$$

All of these equations show that the measurements derived from eccentricity will, when plotted, follow some portion of a sine curve of the form:

$$M = C \sin \{ [B] + [Y] \} \quad [\text{Eq 9}]$$

The semi-amplitude of each such sine curve is defined by the coefficient (C) preceding the sine function. The magnitude of the eccentricity (e) is always part of each coefficient and, except for the Profile measurements, is modified by a factor based on the gear data and the inspection set-up.

The angle of the sine function consists of a number of terms, the final one, represented by 'y' in Equation 9, contains the independent variable in each measurement function. Each of these variables contains (k-1), the number of teeth spaced from the first tooth. For the Index and Pitch measurements, there are no other components since only one point is measured on each tooth. For Profile, the second component is the roll angle at the measurement location (ϵ_M). For Tooth Alignment, it is the distance along the tooth face (x_M). The remaining terms in the angle, shown within the first set of brackets in each measurement equation and represented by 'B' in Equation 9, collectively designate a 'phase-shift' term. All relate to features of the gear and the inspection set-up. Included within these is the term identifying the direction of the eccentricity, namely the angle from the eccentricity to the center of the first tooth at the measurement location, (θ_{eIM}), for Index, Pitch, and Profile, and to the center of the first tooth at the near surface, (θ_{eI}), for Tooth Alignment.

Solving for Eccentricity from Measurement Data.

The process of extracting the eccentricity data from each set of measurement data would then appear to be quite straightforward, as follows:

1. Fit the appropriate sine function to the measurement data and note its semi-amplitude and phase-shift angle.
2. Set the semi-amplitude equal to the coefficient term of the corresponding measurement equation (Equation 1 to 8) and solve for 'e', the magnitude of the eccentricity.
3. Set the phase-shift angle equal to the phase-shift set of terms in the corresponding measurement equation and solve for for ' θ_{eIM} ' or ' θ_{eI} ', the term that locates the direction of the eccentricity.
4. Using this eccentricity information and the proper eccentricity measurement equation, calculate the measurements that would result from eccentricity alone. Then subtract these from the inspection data, leaving only the non-eccentricity components.

The following sections describe this process for each type of measurement. Each description also notes difficulties that may be encountered and procedures for overcoming them. The process for Index and Pitch is already known to the inspection equipment industry but, at present, is used in only the most advanced Index inspection machines. Even there, the treatment is less complete than the description below. The processes for Profile and helical gear Tooth Alignment are not known to be in use and may be original to this paper.

Eccentricity in Index and Pitch Measurements

Figure 2 gives the Left Flank and Right Flank Index and Pitch inspection data on the 15 tooth test gear described in the previous paper [1]. The data in this figure will be used as an example in describing the calculation process.

For a better representation of the Pitch data, the lines with Tooth Number and Index values should be double spaced with the Pitch values printed on the intermediate lines. This would show that each Pitch value represents a measurement between an adjacent pair of teeth and should be assigned a tooth number corresponding to the mid-value of the pair. Thus, the Pitch values shown in the figure alongside Tooth Number 2 are more correctly identified by Tooth Number 1.5. See Table 3 for an example of this representation of tooth numbers.

Step 1. Fit a sine function to the data.

Since each set of data covers a full sine wave cycle, it is possible to use a well known mathematical procedure, the Fourier analysis, to perform this curve fitting operation. After applying this analysis to the Pitch data, the calculated phase-angle must be reduced by one-half the tooth-pitch angle to correct for the first measurement being at the 1.5 tooth number, as explained above.

For the example of Figure 2, this analysis gives the semi-amplitude and phase-shift of each sine function in Table 2, listed under 'Step 1'. The Pitch phase-shift values have been adjusted as noted above.

The Fourier analysis can simultaneously give information about out-of-round conditions or other geometry variations in the gears. These considerations are beyond the scope of this paper.

Step 2. Find the magnitude of the eccentricity.

Each value of sine wave semi-amplitude (C) is set equal to the corresponding coefficient from Equations 1 to 4, and solved for the eccentricity (e) using the appropriate gear and set-up data. Values of these gear and set-up data for the example of Figure 2 were calculated using the equations in Reference [1] and are given at the top of Table 2. Values of calculated eccentricity for each of the four sets of inspection data are listed in Table 2 under 'Step 2'.

Note how closely these values compare to each other. For each flank, the small difference between eccentricity from the Pitch and Index data are due to the rounding errors in the inspection data. Differences between eccentricity from the two flanks are also due to rounding and, possibly, to small measurement error. It may also result from some other slight differences in the flank geometries.

Table 2 also shows a comparison with the value of eccentricity intentionally introduced into the test gear by means of an eccentric arbor. The calculated values are each fairly close to the intentional eccentricity. The differences are within the level of quality of the gear as measured without the eccentric test arbor.

If this procedure is applied to gears with certain unfavorable quality characteristics, there can be some greater difference between Left and Right Flank calculated values of eccentricity. Poor surface texture on the tooth flanks, for example, may have this effect.

Step 3. Find the direction of the eccentricity.

Note: This procedure requires that great care be exercised to insure that direction conventions in reporting the inspection data be identical to those followed in the derivation of the equations.

Each value of the sine wave phase-angle (B in Equation 9) is set equal to the corresponding bracketed angle term in Equations 1 to 4, and solved for the angle (θ_{elm}) which locates the direction of the eccentricity relative to the center of tooth number 1 in the transverse measurement plane. Note that the elements of the bracketed term vary among the four equations, not only in the sign of the angle difference ($\phi_{mt} - \phi_{pmt}$) but also in the 90 or 180 degree adjustment introduced to convert all equations to the form of Equation 9. Note also that the value of this angle difference element is derived, in part, from the value of the set-up feature of measurement diameter. Inaccurate reporting of this diameter will therefore adversely affect the accuracy of individual calculated values of eccentricity direction. However, this element appears with different signs in equations for left and right flanks. Therefore, an average of the calculated direction angles for the two flanks will cancel any error resulting from inaccurate measurement diameter.

The calculated eccentricity direction angles for the data of Figure 2 are shown in Table 2, under 'Step 3'. The values derived from Index and Pitch data for each flank are very close, with the difference due to rounding errors in the reported inspection data. The difference between the two flanks is larger, but still modest. In the case of this test gear, this is probably due to an imprecise value of measurement diameter. The mean value shown is probably the accurate eccentricity direction.

For test gears of lesser accuracy, some difference between direction values for the two flanks is to be expected. In addition to the issue of measurement diameter, there are the various sources of error noted above under Step 2. However, if the difference is substantial, greater than can be explained by such errors, it may be signaling a defect in the gear other than simple radial eccentricity. One type of such a different defect is described in Reference 3. Others are yet to be identified and studied.

The use of such Index (or Pitch) measurements may be extended to detecting Axial Runout (Wobble) in wide-faced spur gears. If Index measurements are taken at two, or better three, spaced axial locations along the gear, and the calculated eccentricity magnitude and