GEAR FUNDAMENTALS

Quality Gear Inspection — Part I

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Introduction

Quality gear inspection means doing the "right" inspections "right." A lot of time and money can be spent doing the wrong types of inspection related to function and doing them incorrectly. As we will discover later, such things as runout can creep into the manufacturing and inspection process and completely ruin any piece of data that is taken. This is one of the most important problems to control for quality inspection.

There are two main reasons for performing any gear inspection:

1. Meeting print specifications. The specifications, such as AGMA 390.03 or 2000-A88 criteria, may be included on the print. They also may be spelled out independently for such things as profile, lead, pitch, etc. The goal of such an inspection is making the parts meet the expectations of the user. Meeting an AGMA quality level has a lot more to do with meeting the rating requirements of the gears than it does with aspects of function such as noise and transmission error.

2. Diagnostic purposes. These inspections are done for the purposes of solving machining problems and controlling noise and transmission error. Many times these will require some nontraditional methods of evaluation.

Photo courtesy of Le Count Inc., White River Junction, VT.

Fig. 1 — Expanding mandrels.

In this article, more time will be spent on the nontraditional diagnostic techniques than on the traditional AGMA level characteristics. AGMA 2000-A88 has much more detail and better definitions for the inspection of gears than AGMA 390.03. Anyone involved in gear specification and inspection should have a copy of AGMA 2000-A88 and become very familiar with the measuring methods and interpretations described within.

Good Data on Purpose

It is very easy to get bad data and not know it. In order to have confidence in the data that one takes, it is imperative to develop good techniques. This section will deal with some of the problems that may be encountered with various measuring methods.

Runout Control. Runout anywhere in the manufacturing or inspection process is one of the most damaging factors affecting gear quality. It will have an impact on anything else that one wants to do or measure. Factors affecting runout include:

Blank Quality. Quality blanks are the foundation upon which a good gear is built. It does no good to expect gear characteristics such as lead, profile and spacing to come out within a few ten-thousandths of an inch when one allows the bore tolerance to vary one or several thousandths of an inch. Certainly, it is easier for an operator to control the size of a simple circle than it is to control that of many gear teeth with a complex form such as an involute. Even a perfect machine can't make a good gear out of a bad blank. Even if it did, the gear wouldn't work in the application, nor would the inspection come out right unless the mounting were duplicated.

Tooling Quality. Good tooling in machining and inspection is a necessity for the manufacture and inspection of quality gears. If a gear is put on a solid arbor, there must be some clearance between the bore and arbor. If there is clearance, there will be some eccentricity, which will result in runout; therefore, it is best to use some kind of expanding arbor. This can fill up the clearance and center the blank on the axis of rotation. Some types of expanding arbors are shown in Figs. 1 and 2. They can consist of expanding collets, hydraulic expansion types, interference ball sleeves or precision expanding jaw arbors that can control runout to .0001 or .0002".

Proofspots. Proofspots are reference bands (axial and radial) that are machined true with the actual bore, journals and shoulders of gear blanks (see Fig. 3). These can be checked while mounted on the machine that finishes the teeth, while mounted on the inspection machine or while mounted in the final application. For even more accurate work, the proofspots are checked and marked for the amount and location of the high point of runout. This high point and amount are duplicated at every step in the process to control the very highest quality gears.

Centers in shafts and their relation to teeth and journals. Unfortunately, most inspection machines for cylindrical gears use centers for the mounting of gears. This is most convenient, but not very accurate. "Murphy's Law" says that even though the journals and teeth are machined from centers, they will never run true again. Gears are rarely run on centers in their applications. They are mounted from the journals, and the teeth should be inspected from the journals. At the very least, the journal should be checked on the inspection machine before the teeth. Some new CNC machines will check teeth relative to the journals, even though they may mount the part from centers.

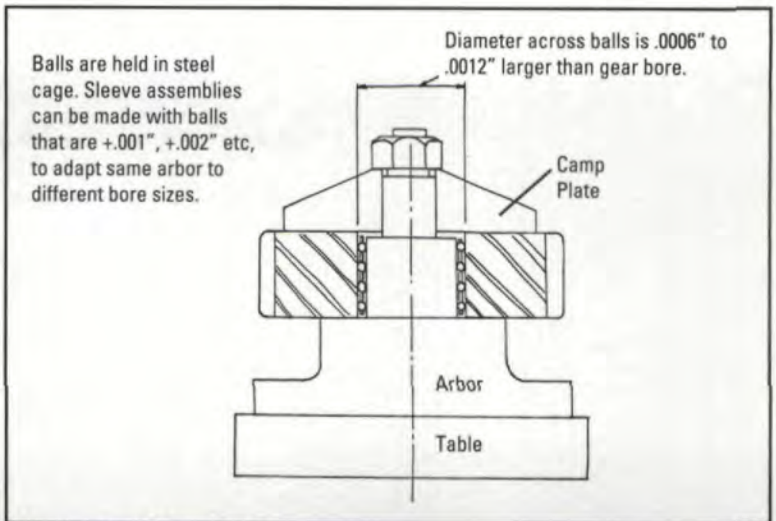

Fig. 2 — Ball sleeve arbor.

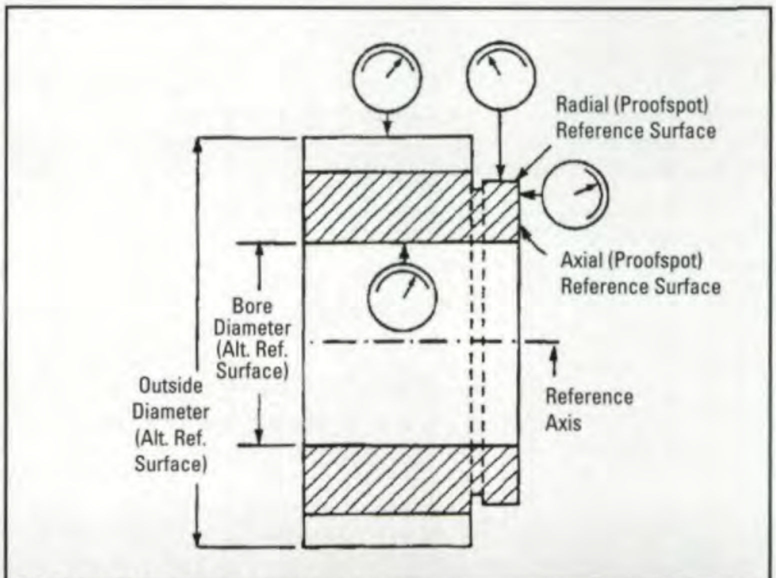

Fig. 3 — Proofspots (reference surfaces).

Remember, if runout exists in the inspection operation, it will influence anything else measured about the gear, such as profile, lead and pitch variation.

Spacing. The term *spacing* is used as a general term to refer to the accuracy with which teeth are positioned around a gear. Spacing has no numerical value and refers only to a group of numerically valued tooth position measurements such as pitch or index. Many of the terms used to describe spacing are very confusing and often misused. For that reason it is important to be careful about what someone is describing. Symbols are very useful in order to keep terms straight. Spacing issues to be addressed in inspection include:

Tooth-to-tooth spacing. This is probably one of the most misunderstood terms. It was used in older versions of AGMA 390 and was an unfortunate choice of words. Many people

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Single-Probe—Precision Method				Two-Probe Method				
A Accumulated Pitch Variation	B Diff. Between Readings in Column A		C Dif. Between Adj. Pitches	D		E Diff. Between Adj. Pitches	F Readings Minus Average	G Accumulated Pitch Variation
Index Variation V_x	Pitch Variation V_p		Spacing Variation V_s	Teeth	Readings	Spacing Variation V_s	Pitch Variation V_p	Index Variation V_x
A 0								0 Ref.
B +2	B minus A	+2	2	A to B	0 →	2	+2	+2
C +2	C minus B	0	2	B to C	-2 →	2	0	+2
D +4 } 6	D minus C	+2	8	C to D	0 →	8	+2	+4 } 6
E -2	E minus D	-6	8	D to E	-8 →	8	-6	-2
F 0	F minus E	+2	4	E to F	0 →	4	+2	0
G -2	G minus F	-2	4	F to G	-4 →	4	-2	-2
A 0	A minus G	+2	0	G to A	0 →	0	+2	0
Total Index Variation $V_{ap}=6$	Max. Pitch Variation $V_p=-6$		Max. Spacing Variation $V_s=8$	$N=7$	-14 Sum -2 Avg.	Max. Spacing Variation $V_s=8$	Max. Pitch Variation $V_p=-6$	Total Accumulated Pitch Variation $V_{ap}=6$

Fig. 4 — Relationships of pitch, spacing and index spacing or accumulated pitch.

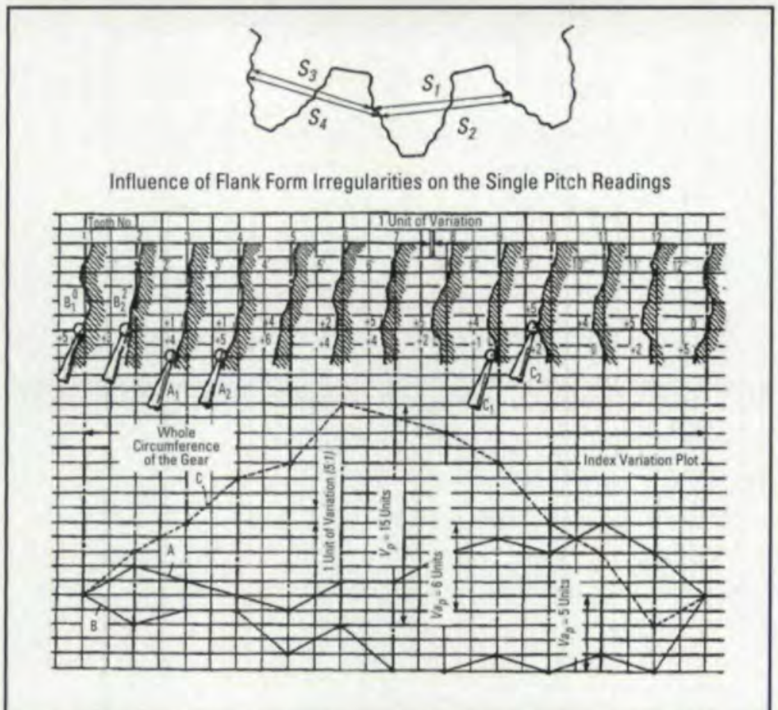

Fig. 5 — Determination of cumulative pitch variation curves (index variation) on the basis of single or span pitch measurements.

(probably most) visualize it as the error between one tooth and the next (involves two teeth). In reality, it is not. It is the difference between one pitch and the adjacent pitch (involves three teeth). A better choice of words would have been *adjacent pitch difference*. AGMA 2000-A88 no longer uses the term tooth-to-tooth spacing. It is now defined as *spacing variation*, V_s. The ISO symbol is f_u, but an earlier proposal, Δf_p, was more descriptive. This parameter has no useful purpose and is not toleranced in AGMA or ISO standards.

Pitch Variation. Pitch variation is the algebraic plus or minus (±) difference in the transverse plane between the true position pitch and an actual pitch measurement. This is the correct measure of the placement of a tooth relative to its adjacent tooth. This factor is most important for evaluating the positional accuracy of a gear and the resulting influence on tooth stresses. The AGMA symbol is V_p and the ISO symbol is f_p. This is the measure of spacing that is toleranced in the AGMA and ISO standards.

Index Variation. Index variation is the displacement of any tooth from its theoretical position relative to a datum tooth. This is the actual location of any tooth around a gear. It is not toleranced, but other values relative to spacing, such as pitch variation and accumulated pitch variation, can be easily interpreted from this data.

Problems With Spacing Measurement. Spacing is usually measured by one of two systems—the *two-probe system* and the *single-probe/index system*. The two-probe system is more likely to produce bad data than the single-probe/index system because of the influence of surface finish (irregularities) on the accuracy of data. The influence is greater on calculation of accumulated pitch variation than it is on pitch variation. Fig. 4 is an illustration from Section 9 of AGMA 2000-A88. It shows the correlation between a single-probe/index measurement and a two-probe measurement of the same gear. In this case, the gear is a theoretical one and has perfect finish. As one can see, in columns A, G, B and F, the results are the same for either measuring method. However, in reality, the results will never be the same, and the worse the finish, the worse the correlation.

More realistic results are evident in the data shown in Fig. 5. This is from Appendix E of AGMA 2000-A88. The upper part of the figure shows what happens because of surface irregularities to the span distance between two probes placed at slightly different locations on the teeth. The bottom part of the figure shows the numerical results of measuring a gear three times with the probes located in different positions. Because of surface irregularities, there will be a greater scatter in the results from the two-probe method. The difference is caused by the accumulation of surface measuring errors as well as pitch errors in the calculation process of the two-probe system. This calculation is not necessary in the single-probe system. The reading for each tooth is direct, and surface errors affect only that one reading.

Measuring the gear several times with the probe in a slightly different position and then averaging the results will give a more accurate answer for the true pitch and accumulated pitch values. This would be true for either system.

Another advantage of the single-probe data is that it gives a direct visual picture of the placement of each tooth around a gear. Pitch variation is the distance between any two adjacent readings, and accumulated pitch variation is the total distance between the highest and lowest reading. When using the two-probe system, it is necessary to calculate the average measured pitch, subtract this from each reading to obtain pitch variation values, and then accumulate the pitch variation readings to obtain the accumulated pitch.

Problems With Size Measurement. The specified size of gear teeth, their circular tooth thickness, is not measured directly. It is usually measured by one of four other means: vernier tooth calipers (chordal tooth thickness), over pins or wires, span measurement (base tooth thickness) or by double-flank composite methods, which measure functional tooth thickness (see Fig. 6).

The first three of these methods also have the limitation that the measuring device only touches a few points on one or a few teeth. Therefore, they may not find the largest tooth size around the gear. They also measure the tooth size independent of the rotational axis of the gear. Even if the tooth size is correct, runout will vary the functional tooth thickness. Some teeth will be functionally larger than others if they are at the high point of runout. It is necessary to make allowances for other variations in tooth shape and position (involute, lead, runout, etc.) in relation to gear quality level (see Fig. 7). If this is not done, the gear may run out of backlash with its mate.

The double-flank composite method will find the largest functional tooth thickness anywhere around the gear. It is probably the best

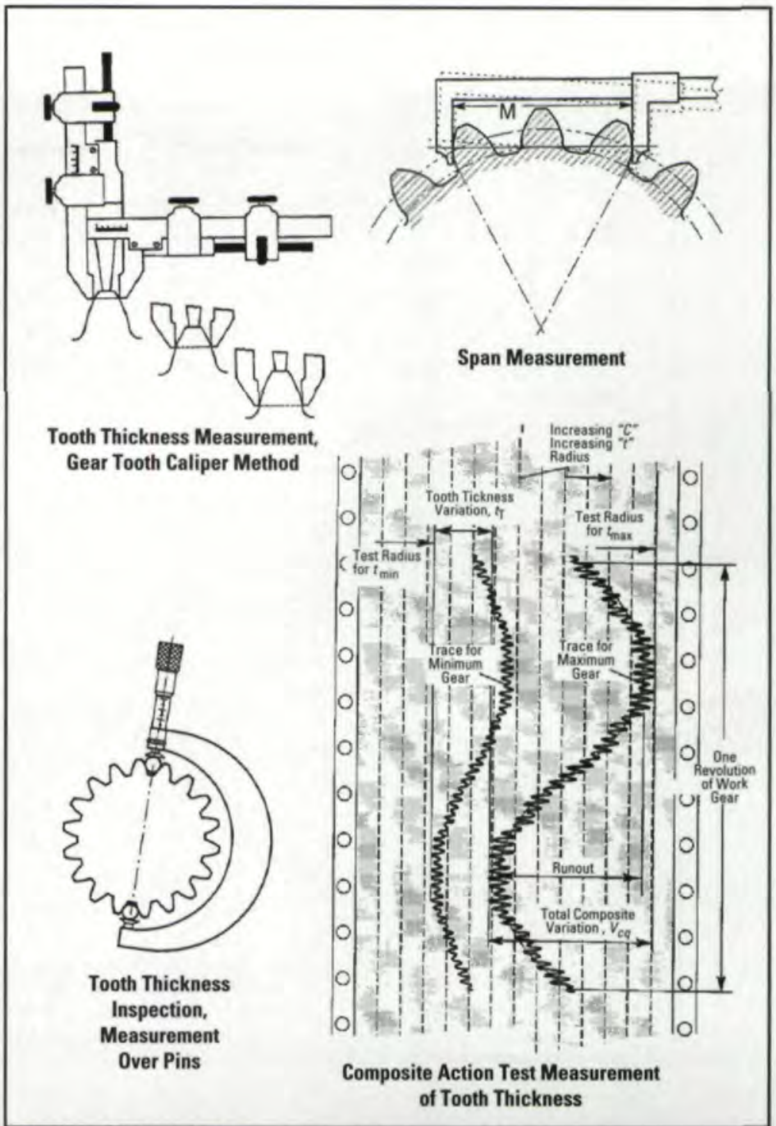

Fig. 6 — Method of size measurement.

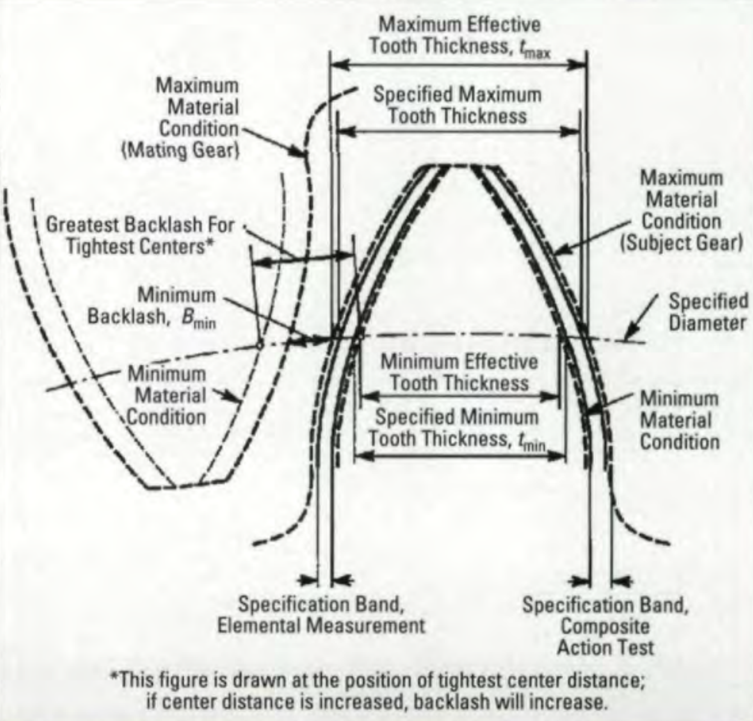

Fig. 7 — Tooth thickness, transverse plane.

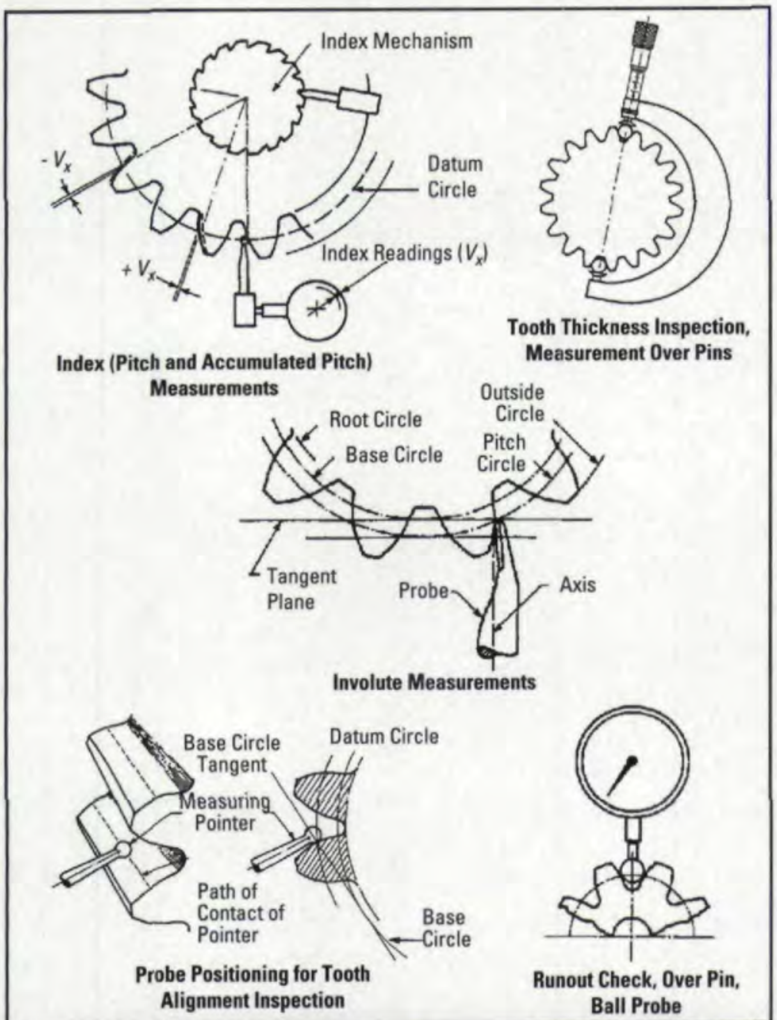

Fig. 8 — Elemental measurements.

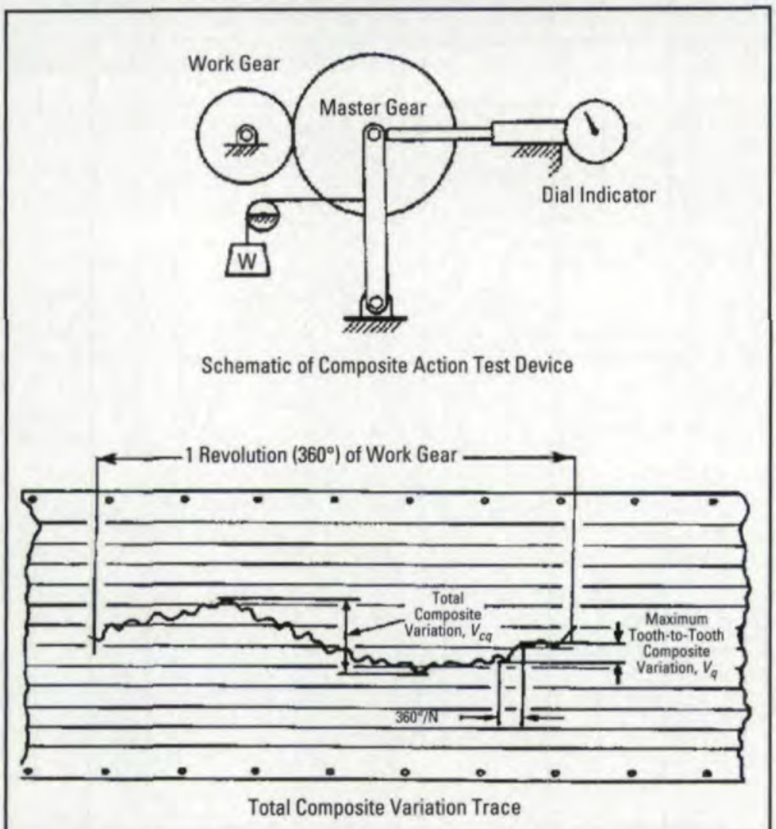

Fig. 9 — Double-flank composite action measurement.

method for finding the size of gear teeth. Refer to AGMA Standard 2002, *Tooth Thickness Specification and Measurement*, for a more detailed treatment of this subject.

Elemental vs. Composite Measurement. There are two general methods in use for the measurement of gear quality. These are the elemental and composite methods. Further, there are two different composite methods—double-flank and single-flank.

Elemental Methods. Elemental measurement involves the measurement of discrete aspects of gear quality—such as involute, tooth alignment (lead), pitch variation, runout, accumulated pitch variation and tooth size—by using a small probe to explore the individual characteristic (see Fig. 8). It is very useful for medium-size gears, but difficult to use for very fine pitch or very large diameter gears. The AGMA standard limits elemental tolerances to pitches coarser than 20 DP. However, it is possible to make elemental measurements as fine as about 100 DP with some equipment. The upper limit for diameter is generally about 40". This limit is imposed by a lack of available inspection machines, although there are a few that can go larger.

These methods are generally useful for diagnostic purposes as well as for quality determination.

Double-Flank Composite Methods. Double-flank measurements are made by rolling the test gear in tight mesh with a master gear while detecting center distance variation (see Fig. 9). The quality determination for the same gear may come out different if it is measured by elemental methods. For this reason, both methods should not be used for the same part. The maker and user should agree on the method to be used.

Advantages. This method provides a fast check that uses inexpensive equipment. It is good for the determination of runout prior to any subsequent finishing of the gear teeth, and it is excellent for the determination of functional tooth thickness.

Disadvantages. It measures a composite of all characteristics and is not as useful for diagnostics. It can tell when teeth are conjugate (very low tooth-to-tooth composite), but it is not very good at telling how non-conjugate the teeth are. It measures both sides of the teeth at the same time and can produce some strange tooth-to-tooth results. It is also possible to have some very bad involute shapes but not have this method produce large tooth-to-tooth variations.

It also measures the characteristics of gear quality in a radial direction (center distance variation). Gears don't operate this way. They operate in a tangential direction.

When gears are made by certain finishing operations, such as shaving and abrasive hobbing, it is possible to have a double-flank measurement show very little runout (maybe a few ten thousandths of an inch) when in reality it has several thousandths of an inch accumulated pitch variation. Remember that gears function tangentially. Runout is a radial measure, while accumulated pitch is a tangential measure (see Fig. 10).

Single-Flank Composite Methods. Single-flank measurements are made by rolling two test gears or a test gear and a master gear together at their proper mounting distance and with backlash. Transducers measure the angular motion and record any characteristics of nonuniform motion (see Fig. 11). This is a true tangential measurement and is indicative of the functional characteristics of the gear. This nonuniform motion is called transmission error.

Advantages. Single-flank measurement is a truly functional, tangential measure. It is good for diagnostic purposes. It is especially useful for the measure of profile shape and conjugacy as well as for accumulated pitch variation.

Disadvantages. It is not good for measuring tooth alignment (lead) and size. It is a slower test than the double-flank method. It uses equipment that is more expensive and not as readily available.

Which Inspections to Perform?

Obviously, if a print calls for certain inspections, these must be done. However, one also should think of what are the most important characteristics desired of the gears. Quietness? Positional accuracy? Strength and durability? Size? Some combination of these? The greatest measurement effort and best techniques should be applied to the most important parameters. For example, if positional accuracy is most important, a lot of time should not be spent measuring runout. It can be very misleading. See Fig. 12 for a chart of recommended measuring methods. Standards now in process with

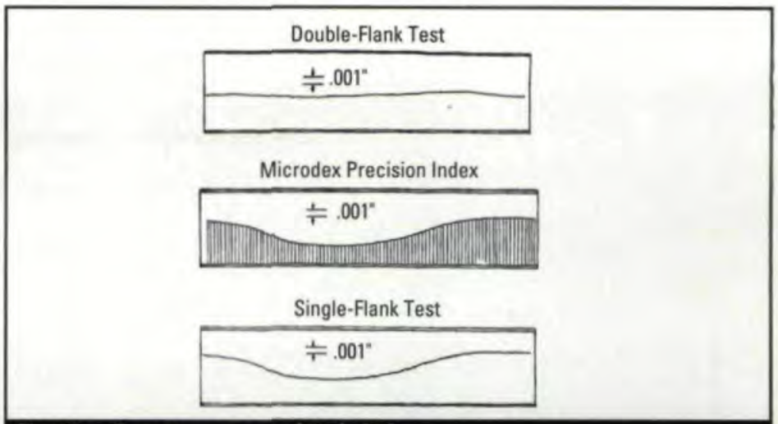

Fig. 10 — Runout vs. accumulated pitch.

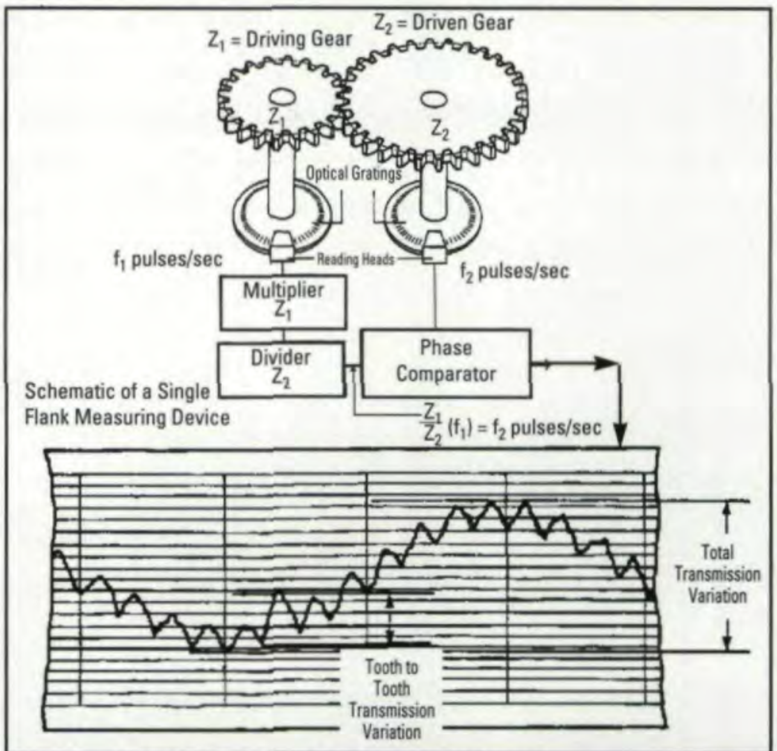

Fig. 11 — Single-flank composite action measurement.

Measurement Method Order of Preference 1, 2, 3	Important Quality Criteria: Noise	Accuracy	Strength or Surface Durability	Tooth Size	Finish
ELEMENTAL					
Profile	2	2	1		
Lead			1		
Pitch Variation	3	1	2		
Acc. Pitch Var.		1			
Runout		2			
SIZE					
Funct. Tooth Thick.				1	
Span				2	
Over Pins or Wire				2	
Vernier Tooth Mic.				3	
DOUBLE-FLANK COMP.				1	
Tooth-to-Tooth	3	3			
Total Comp.		3			
Funct. Tooth Thick.				1	
SINGLE-FLANK COMP.					
Tooth-to-Tooth	1	1			
Total Comp.		1			
MICROFINISH					
Roughness-Stylus					1
WAVINESS					
Contact Pattern					2
Single Flank					1

Fig. 12 — Quality criteria vs. measuring method.

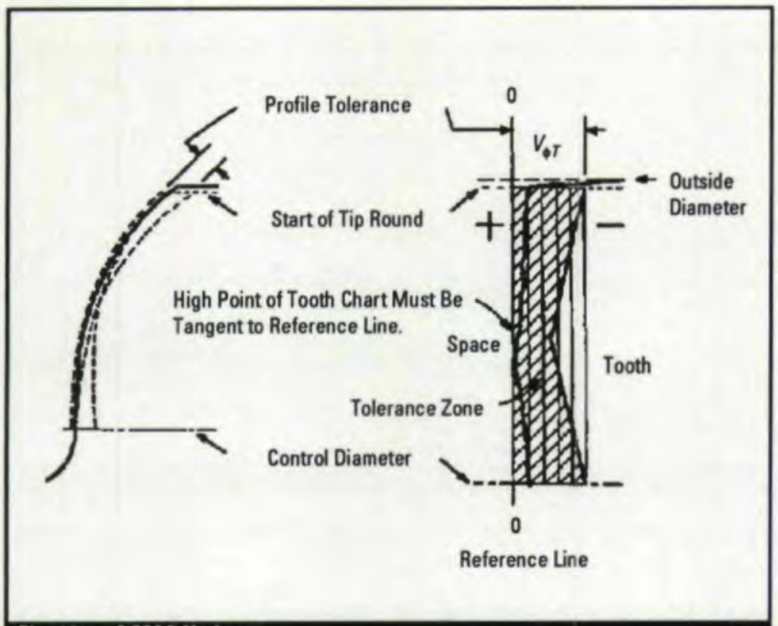

Fig. 13 — AGMA K chart.

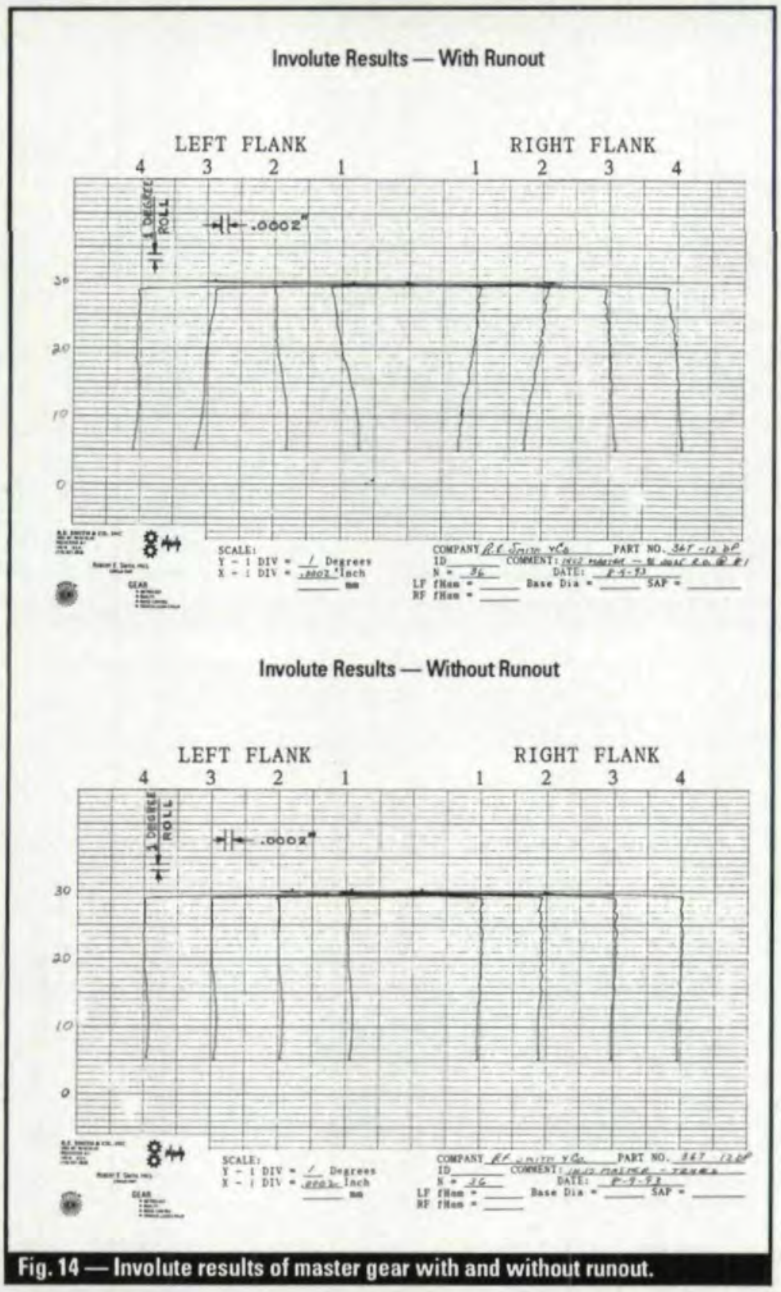

Fig. 14 — Involute results of master gear with and without runout.

the ISO accuracy committee include one that defines "families" of inspection tolerances that apply to various applications. One should put the most effort on the proper group of tolerances as it applies to the application. In other words, spend your measurement money wisely.

Question the Specifications. It is wise for the gear maker to spend some time with the gear user to arrive at the most important specifications and measuring methods. The importance of agreement on these points can be shown by example: It is not unusual for someone to specify an AGMA Q8 quality level but want to hold tooth thickness to a tolerance of .001". The problem is that the amount of runout allowed by level Q8 may not be compatible with the specified tooth thickness tolerance. It may be necessary to make a Q10 or higher gear in order to hold the tooth thickness variation within the specified tolerance. This costs more money.

Question the Standards. Many times the print will only call for an AGMA Q number. These quality levels have been established primarily for gear rating evaluation. Depending on the application, this specification will not necessarily guarantee satisfactory performance. For example: if a positional accuracy is the prime concern, this information alone will not be enough. The AGMA Q number only specifies runout and pitch variation. Accumulated pitch and pitch variation are better measures. Also, profile and lead are controlled by K charts. These K charts give a very broad control of profile and lead. They have to be broad to allow for the effects of runout on the various teeth around a gear. See Fig. 13 for a description of a K chart.

Fig. 14 shows involute charts of a master gear with and without runout. This same thing can happen with tooth alignment or lead charts. In other words, involute isn't being evaluated separately. The K charts are evaluating a combination of involute and runout. ■

Editor's Note: *The second part of this article, covering diagnostics, measuring equipment and inspection practices among U.S. competitors, will appear in the next issue.*

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