Single-Flank Testing of Gears

Robert E. Smith

Management Summary

This article was originally published 20 years ago, in *Gear Technology*'s first issue. It describes a method of evaluating the smoothness, or lack of smoothness, of gear motion. This lack of smoothness of motion, known as "transmission error," is responsible for excitation of gear noise and problems of gear accuracy and sometimes has a relationship to gear failure.

This method of evaluation was not in very common usage 20 years ago and, unfortunately, even now is very much underused.

The article is still timely today. This method has now been included in some gear accuracy standards, such as AGMA and ISO. Also, it is a technique that is used often by the author in the solution of gear noise problems.

Presumably, everyone who would be interested in this subject is already somewhat familiar with testing of gears by traditional means. Three types of gear inspection are in common use: 1.) measurement of gear elements and relationships, 2.) tooth contact pattern checks and 3.) rolling composite checks. Single-flank testing falls into this last category, as does the more familiar double-flank test (see Fig. 1).

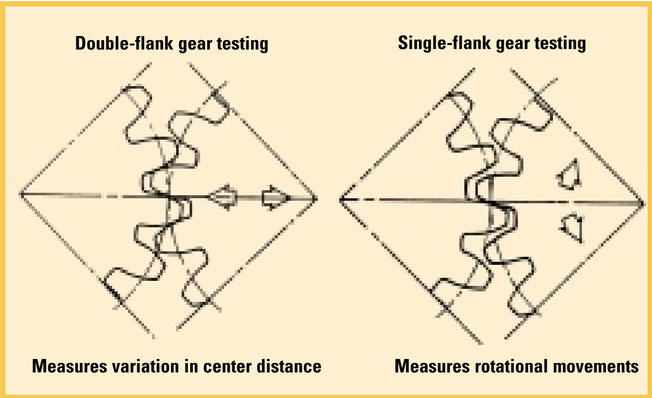


Figure 1—Composite gear testing.

As an introduction to the basic understanding of the subject, most of this article relates to the simple case of inspecting spur gears. The interpretation of data, relative to helical gears, is a little more complex, but the general principles apply.

With single-flank testing, mating gears roll together at their proper center distance with backlash and with only one flank in contact. Testing gears in this manner more closely simulates operation of the gears in their application than any other means of evaluation. Gears can be tested by pairs, or with master gears.

The single-flank test is run using optical encoders, which measure rotational motion (angular displacement error). Encoders may be attached to the input and output shafts of a special machine for testing pairs of gears. The encoders may also be used portably by attaching them directly to the input and output shafts of an actual gear box so as to inspect the quality of a complete train of gears.

Data from the encoders is processed in an instrument that shows the accuracy or smoothness of rotational motion resulting from the meshing of the gears (transmission errors). This data can be directly related to portions of involute or profile errors, pitch variation, runout and accumulated pitch variation. Probably the most important aspect of single-flank testing is that it permits measurement of profile conjugacy, which is the parameter that most closely relates to typical gear noise.

Single-flank testing is not a panacea. Lead or tooth alignment variation of spur and helical gears cannot be measured directly by this method. Lead errors do, however, influence motion transmission errors. These result from profile variations, due to the influence of overlap or increased contact ratio. Likewise, in the case of bevel or hypoid gears, tooth contact pattern checks are important to the development of tooth shape to allow for deflection characteristics under load. Lead or spiral is best measured by elemental checks or by tooth contact pattern checks.

Figure 2—Gleason Corp.'s 600HTT Turbo Tester® is an example of a machine able to perform single-flank testing.

Figure 2 shows a typical single-flank measuring machine. Figure 3 shows its principle of operation. The two motions which are to be compared are monitored by circular optical gratings. Each grating produces a train of pulses having a frequency which is a measure of the angular movement of each corresponding shaft and hence of each gear mounted thereon.

Pulse frequencies from each grating are usually different because the gear ratio is not normally 1:1. It is, therefore, necessary to modify the frequency from shaft Z_1 based upon the frequency from shaft Z_2, which is hereby established as the reference frequency. The signal from shaft 2 has a frequency of f_2, which is equal to:

$$f_2 = f_1 \text{ x } \frac{Z_1}{Z_2}$$

where: Z_1 = the number of teeth in the gear on shaft 1 and
Z_2 = the number of teeth in the gear on shaft 2.

However, f_2 has superimposed on it a frequency modulation due to transmission errors of the gears under test. Therefore, the pulse train coming from the grating on shaft 2 will have small differences in phase from the pulse train for shaft 1. This phase difference between the two represents the amount of error in the gears being tested.

Phase differences of less than one arc-second can be detected. This difference is recorded as an analog waveform and comes out of the instrument on a strip chart, as shown in Figure 4.

Gears with perfect involute tooth forms will roll together with uniform motion. When pitch errors or involute modifications (intentional or otherwise) exist in a gear, nonuniform motion or transmission errors will result.

In some lightly loaded applications, perfect involutes are desirable for noise control. However, profiles are often modified to obtain a compromise between load carrying capabilities and smoothness of roll or transmitted motion. Such modifications produce predictable, intentional variations on graphic analysis outputs. These variations must be acknowledged when interpreting the graphs. Figure 5 shows three typical tooth shapes and their resulting motion curves. Figure 5a is a perfect involute

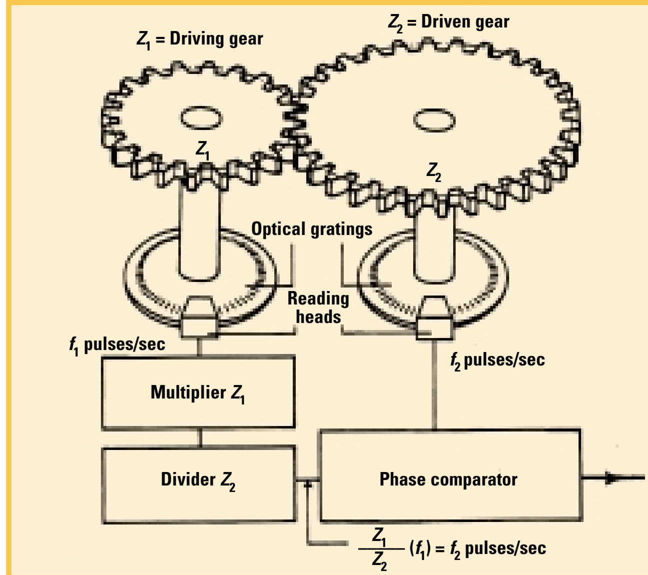


Figure 3—The principle of a single-flank measuring machine.

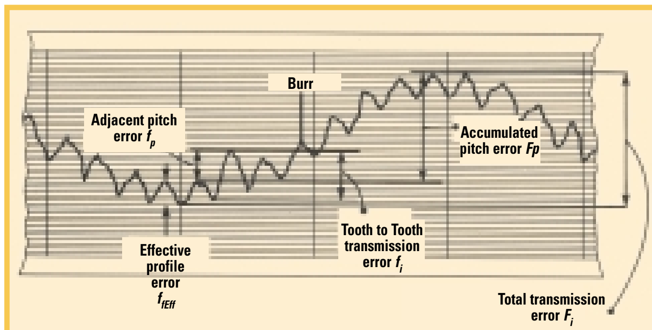


Figure 4—Individual errors revealed by single-flank testing.

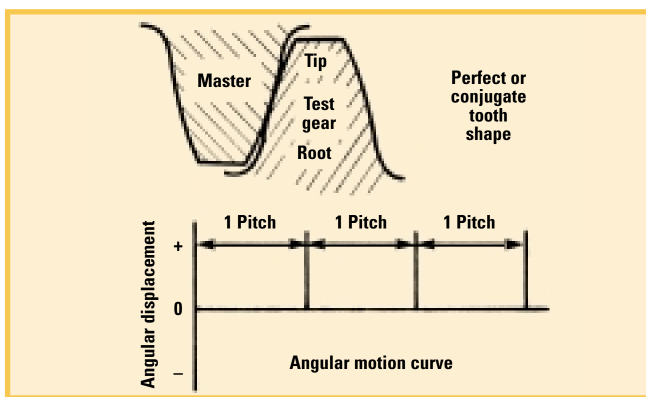
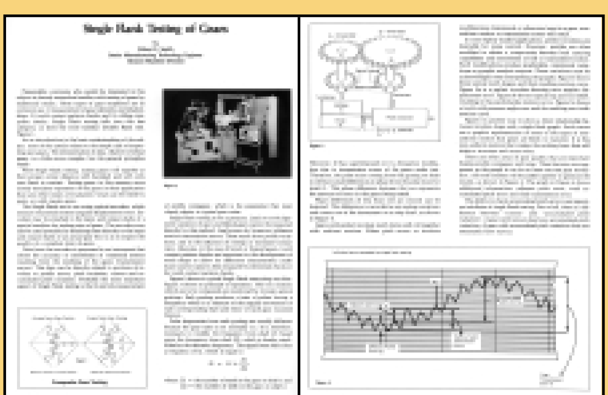


Figure 5a—A perfect involute tooth showing zero angular displacement error.

FLASHBACK TO 1984

In 1984, the Macintosh computer was introduced during Super Bowl XVIII. The movie "Amadeus" won the Academy Award for best picture. The musical group Van Halen was at the top of the music charts and this article by Robert E. Smith first appeared in *Gear Technology.*



Robert E. Smith

is president of R.E. Smith & Co. Inc., a gear consultancy in Rochester, New York, U.S.A. A mechanical engineer, he's worked extensively with single-flank testing equipment and on gear noise evaluation since the late 1950s. He's also written several AGMA technical papers on transmission error and gear noise. Twenty years ago, Smith was a technical author in Gear Technology*'s first issue. Since 1991, he's been one of our technical editors.*

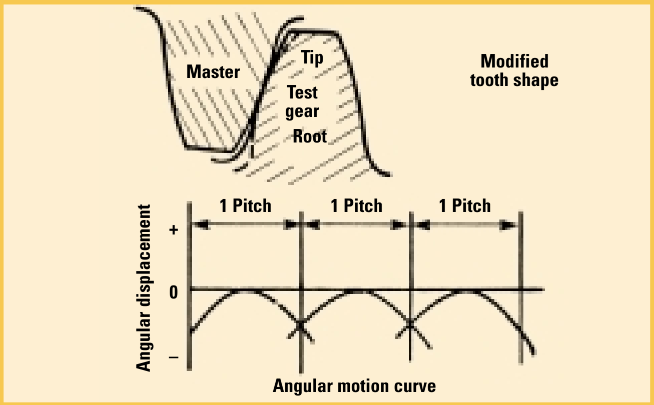


Figure 5b—An involute tooth with tip and root relief that result in parabola-like motion curves.

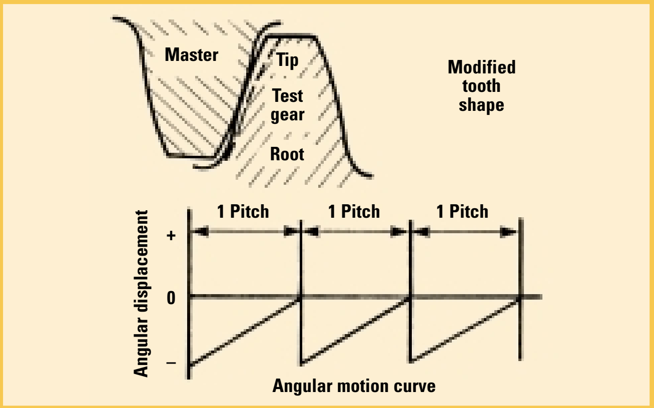


Figure 5c—An involute tooth with pressure angle error that results in saw tooth motion curves.

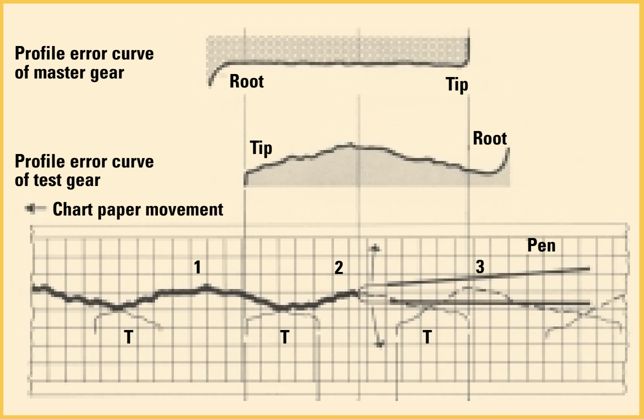


Figure 6—Direct relationship between an involute tooth and a single-flank graph.

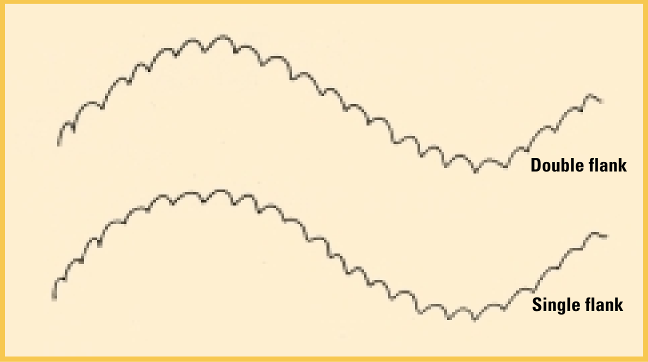


Figure 7—Typical recording of gear with runout.

showing zero angular displacement error. Figure 5b shows gradual tip and root relief, typical of shaving operations, that result in the parabola-like motion curve. Figure 5c shows a tooth with pressure angle error and the resulting saw tooth motion curve.

Figure 6 is another way to show a direct relationship between involute shape and a single-flank graph. Such curves are graphic representations of some of the types of nonuniform motion that gears are likely to transmit. It is this nonuniform motion that creates the exciting force that will shake a structure and cause noise.

There are other areas of gear quality that are important besides profile conjugacy and noise. These become more apparent as the graph is run for at least one test gear revolution. All tooth meshes will be added together to generate the results, as shown in Figure 4. The graph in Figure 4 shows additional information: adjacent pitch error, total accumulated pitch error and total transmission error.

The ability to check accumulated pitch error is an important attribute of single-flank testing. First of all, there is a difference between "runout" and "accumulated pitch variation." A gear with runout has accumulated pitch variation. A gear with accumulated pitch variation does not necessarily have runout.

Runout occurs in a gear with a bore or locating surface that is eccentric from the pitch circle of the teeth. Runout is shown as a variation in depth of a ball type probe as it engages each successive tooth slot. Or, it can be a large total composite error if observed on a double-flank tester.

A gear can be produced, by various means, that will have no runout, as described above, and will show little or no reading by the ball check. It could, however, have large accumulative pitch errors. This can happen when a gear is hobbed with runout and then shaved or ground on a machine that does not have a rigid drive coupling the tool to the workpiece.

When the gear is hobbed with an eccentric pitch circle, the slots are at different radii and angular positions. When the gear is shaved, it is run with a tool that maintains a constant, rigid center distance, but is not connected to the workpiece by a drive train. Therefore, all slots are now machined to the same radius, from the center of rotation, and are displaced from true angular position by varying small amounts. The resulting gear has very small amounts of individual pitch errors, but has a large accumulated pitch error, which the single-flank tester responds to.

These accumulative pitch errors have all the undesirable effects of a gear with traditional runout. It would check "good" by either a ball check or a double-flank composite test. Accumulative pitch errors can only be found or properly evaluated by a precision index/single probe spacing checker, or by a single-flank composite test.

Figures 7 and 8 are intended to help illustrate the advantages of single-flank vs. double-flank composite tests.

Figure 9 is an extreme example, whereby the wrong number of teeth is cut in the part. Double-flank composite testing will indicate that the part is acceptable, but single-flank testing will reject it.

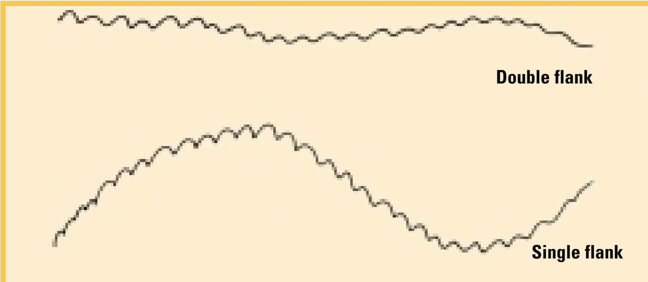


Figure 8—Typical recording of gear with accumulated pitch variation, as can be produced by abrasive hobbing or hobbing/shaving process.

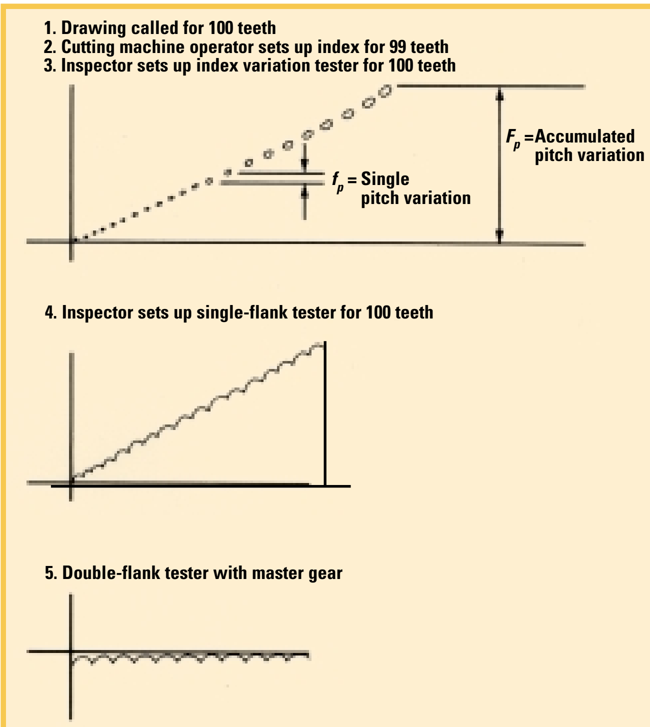


Figure 9—An extreme example to show the advantages of single-flank vs. double-flank composite tests.

Conclusions

Single-flank testing can check all elements of gear quality, except possibly lead/helix or spiral angle error, much faster and more thoroughly than individual elemental tests or double-flank composite tests. This method:

1. Explores, essentially, all areas of all teeth.
2. Finds all kinds of runout, including accumulated pitch variation (hidden runout).
3. Measures the combined profile errors on bevel gear teeth that cannot be measured adequately by tooth contact patterns or by elemental gear measurements.

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