TWO-PROBE PITCH INSPECTION METHOD FOR LARGE GEARS
Highlighting merits of the two-probe index inspection method for large gears with a cursory review of the single-probe pitch inspection methodology, breakdown of tooth index characteristics, and a cross-reference of the single- and two-probe inspection methods.

By YEFIM KOTLYAR and CHRISTOPH DONNER

A gear’s pitch (a.k.a index or spacing) accuracy is one of the most fundamental gear characteristics affecting its performance. Pitch errors affect the transmission accuracy, vibration, noise, and even the load carrying capacity. No wonder gear designers, manufacturers, and users pay close attention to pitch quality. Nowadays, there are many different pitch measuring technologies available to verify pitch accuracy: Specialized gear measuring centers, CMMs, optical gages, laser gages, and more. This article will provide a cursory review of pitch characteristics, overview of a single and a two-probe pitch measurement — the two distinct pitch inspection methodologies, and will discuss some beneficial aspects of the two-probe inspection method as applied to large diameter gears.

GEAR PITCH CHARACTERISTICS

Most, if not all, widely used standards, e.g. AGMA, ISO, DIN, etc. recognize and provide tolerance systems for at least three major pitch characteristics. The latest ANSI+AGMA+ISO+1328-1-B14 standard labels these three characteristics as: Cumulative Pitch Deviation $F_p$, Pitch Deviation (a.k.a Pitch Variation) $f_p$, and Adjacent Pitch Difference (a.k.a Spacing Variation) $f_u$. Other naming conventions for these three pitch characteristics were also accepted in different times and different countries. While labels for the three characteristics were different, the substance of these characteristics remained the same.

Pitch deviation, $f_p$, is the difference between the actual distance between two adjacent teeth and the ideal distance. The ideal circular distance between two teeth is the distance between adjacent teeth that are equally spaced around circumference and it equals the circumference of the measured diameter — typically as close as possible to the pitch diameter — divided by the number of teeth. It is depicted as $p_{M}$ on Figure 1. The pitch deviation for this particular adjacent tooth pair, $f_{pi}$ also shown on Figure 1, indicates the difference between the actual circular distance between the two adjacent teeth and the ideal distance. It has a positive sign because the actual distance is larger than the ideal (theoretical) distance.

The measurement is conducted for all gear teeth pairs and the maximum deviation is reported as maximum Pitch Deviation error. The top graph on Figure 2 depicts 18 measurements and individual values of pitch deviations between all adjacent tooth pairs. The maximum absolute value between flanks 16 and 17 would be reported as the maximum pitch deviation error located on pitch number 17.

Cumulative Pitch Deviation is plotted by algebraically adding individual pitch deviations as depicted in Figure 3. The difference between two extreme points of the graph is reported as the Total Cumulative Pitch Deviation error, $F_p$.

Adjacent Pitch Difference, $f_u$, (a.k.a spacing varia-
Some large gear manufacturers attempt to qualify their universal gear inspection machines by comparing Single Probe Pitch inspection results with the Two-Probe inspection results.

Adjacent Pitch Difference is the difference between the actual adjacent pitches. It does not have an algebraic sign, as the absolute values of the differences are determined. Adjacent Pitch Difference is determined for every two adjacent pitches and the maximum absolute value is reported as max Adjacent Pitch Difference, see bottom graph of Figure 2.

**PITCH INSPECTION METHODS**

Gear pitch inspection has a long history. Mechanical pitch inspection devices preceded computerized universal gear inspection machines that are so familiar to us nowadays. While there are many different technologies available for measuring pitch errors, e.g. specialized gear measuring machines, CMM, optical gages, laser gages, and more, there are only two fundamental pitch inspection methodologies:

- Single-probe method.
- Two-probe method.

Most pitch inspection technologies available today, such as universal gear inspection machines, use the single probe method. While this method can provide an accurate and repeatable inspection for small and medium size gears, it has certain limitations when it comes to larger gears. In fact, for a given universal gear inspection machine, there is a linear relationship between the pitch inspection accuracy and the gear diameter.

The single-probe method, see Figure 4, relies on the rotary encoder's angular measurement that is converted to linear measurement at the gear pitch diameter. The inspection accuracy therefore depends on the encoder's diameter and resolution. These two features are constants for a given inspection system. In addition, however, the inspection accuracy depends on the size of the gear, specifically on the radial distance between the machine's rotary encoder and the gear's pitch diameter. The larger the gear, the farther the gear's pitch diameter is from the encoder, the less accurate is the measurement.

The single-probe pitch inspection process starts with setting the angular datum for all measurements. The probe is moved to the measuring diameter, typically the pitch diameter. After that the gear is rotated until the probe reaches the optimum deflection for its zero reading. The zero probe reading signals the system to record the angular reading of the rotary encoder. The rotary encoder reading for the first tooth is set as the datum reference for all subsequent measurements. The actual encoder readings are compared with the expected angles (determined as the first tooth datum angle plus ideal angular advance to the corresponding tooth). The angular difference between the encoder reading and the expected angle converted to the linear displacement yields the Cumulative Pitch error for each respective tooth.

\[ F_{pi} = dA \times Rm \]

Where:
- \( F_{pi} \): Cumulative pitch error for the respective tooth i.
- \( dA \): Difference between the rotary encoder reading and the expected angle, radians.
- \( Rm \): Gear radius where probe contacts the gear surface, typically close to the pitch radius.

Whatever measuring inaccuracy \( dA \) contains, it is always magnified by the gear's pitch radius. The resulting inaccuracy of \( F_{pi} \) measurement is proportional to the gear's pitch diameter. The larger is the gear diameter, the greater the measuring system inaccuracy. Even when a high precision encoder with one second resolution is used, the measuring inaccuracy can be significant for large gears. Figure
5 quantifies measuring errors depending on gear diameter when a high — one second — resolution encoder is used.

The two-probe method measuring accuracy, however, does not depend on the quality of the rotary encoder, nor does it depend on the gear’s pitch diameter and therefore provides measurements with consistent inspection accuracy regardless of the gear size. Figure 6 shows one of the earlier mechanical instruments that conceptualizes the Two-Probe measuring principle well. One probe (on the right) has a mechanically fixed reference position; it is rigidly fixed to the inspection unit housing. The other probe moves relative to the fixed probe and measures the distance between two adjacent teeth. This process is repeated for every single pair of adjacent teeth. Thus, every preceding tooth is the datum for the measurement of every successive tooth.

The measurements for every pair of teeth are recorded in a table and the three pitch characteristics (Fp, fp, and fu) are determined based on math model as described in the following section:

**CROSS-REFERENCES OF SINGLE AND TWO-PROBE PITCH INSPECTION METHODS**

While there are three characteristics under the auspices of the pitch error (Fp, fp, and fu), they are mathematically interrelated, thus only one set of measurements is required to determine all three characteristics.

Each inspection method is aided with a respective math model for converting the measurements into the three commonly used pitch characteristics: Cumulative Pitch Deviation (Fp), Pitch Deviation (fp), and Adjacent Pitch Difference (fu).

An example of pitch inspection by both the single and the two-probe methods as well as a cross-reference between the two methods can be found in the legacy AGMA 2000-A88 standard, “Figure 9-9 Relationship of Pitch, Spacing, and Index Spacing, and Index Spacing, or Accumulative Pitch” [2]. The table shown in Figure 7 is mostly based on that example.

The left three columns (A, B, C) depict the single-probe math model to determine Fp, fp, and fu, as the single-probe measurements directly provide the Cumulative Pitch errors. The Cumulative Pitch errors are depicted in column A highlighted by the yellow background. The Total Cumulative Pitch error is determined by the difference between the max and min readings 4+(-2)=6, see pink background.

Column B shows the Single Pitch Deviation, fp. Each Single Pitch Deviation is determined by subtracting the average value from the individual readings.

Column C depicts the Adjacent Pitch Difference, fu. It is determined by subtracting adjacent Single Pitch Deviations. Absolute values are used as the Adjacent Pitch Difference does not have a sign. The max value represents the Max Adjacent Pitch Difference. In this particular example, two Adjacent Pitch differences have the same value “8” marked with pink background.

The right four columns (D, E, F G) depict the two-probe math model to determine Fp, fp, and fu.

The measuring results are depicted in column D highlighted by yellow background. In addition to individual measuring results, the average is calculated, as shown at the bottom of the column.

The Single Pitch Deviation, fp, is determined next by subtracting the average value from the individual readings. The results are depicted in column F.

Cumulative Pitch Deviation, Fp, is determined by accumulating the Single Pitch Deviations, see column G.

Finally, the Adjacent Pitch Difference, fu, is determined by subtracting adjacent Single Pitch Deviations. The results are depicted in column E.

Assuming that gears are indicated to similar runout conditions, these two inspection methods should produce very similar results.

---

**Figure 6: Two-probe pitch inspection concept [4].**

**Figure 7: Cross reference of single- and two-probe pitch inspection methods [2].**

**Figure 8: D & P ES4100.**

---
PITCH INSPECTION ON LARGE GEARS

The Two-Probe Portable pitch testers are frequently used to address several challenges arising with the pitch inspection of large diameter gears.

One challenge is presented when the gear is larger than the inspection capability of a typical universal gear checker. The Two-Probe portable gear checker has no maximum gear size limitation and therefore can be employed for the oversized gear pitch inspection.

Second, large gears are more difficult and expensive to move back and forth between cutting and inspection machines. In addition, when the gear is moved from one machine to another multiple times, the important coincidence of the gear’s datum (e.g. journal, bore, centers, etc.) and the actual center of gear rotation on the cutting and inspection machines can be compromised and produce erroneous inspection results.

Third, and the most significant challenge, is when a large gear is manufactured for high precision and pitch sensitive applications. The pitch inspection for these gears using the Single Probe method could be compromised as the encoder’s inaccuracies e.g. resolution and others errors would be magnified by the gear’s pitch radius.

Despite the fact that most of the pitch inspection technologies today use the single-probe method, some companies that deal with most sensitive pitch accuracy applications for large gears prefer the two-probe pitch inspection method because it is portable, has no maximum gear size limitation, and most importantly yields remarkable and consistent accuracy and repeatability. In fact, some large gear manufacturers even attempt to qualify their universal gear inspection machines by comparing single probe pitch inspection results with the two-probe inspection results.

MODERN PORTABLE TWO-PROBE PITCH TESTER

A modern automatic two-probe pitch tester uses the same principle as the mechanical tester depicted on the Figure 5. However, instead of the mechanical rigid probe for creating the datum, see the right probe shown in Figure 5, a modern automatic two-probe pitch tester uses one of the two precision electronic probe to establish the datum for every pitch measurement, see Figure 8. While the gear rotates slowly and continuously (or intermittently) the two probes advance into the tooth gaps, take the pitch measurement, and quickly retract after the measurement is taken. The advancement, measurement, and retraction of two probes are automatically repeated for every single pair of gear teeth.

In the second half of the 20th century, at least two companies — Maag and Hoefler — made automatic electronic two-probe pitch testers. Today, however, neither of these two companies produces this type of product.

Today, however, there is one company that makes modern automatic portable pitch testing equipment utilizing the two-probe method: Donner & Pfister AG (D&P), founded in 1989 by Meinrad Donner, the inventor of Maag ES401 automatic pitch tester. Through the years, D&P also made improvements and kept pace with the computer technology developments. Their newest D&P ES4100-2 pitch tester, Figure 9, includes probes with digital scales, wireless WiFi connection with a commercial tablet or a computer, and invar base for reducing the thermal effects on accuracy.

EXAMPLES OF THE TWO-PROBE PITCH INSPECTION METHOD REPEATABILITY

Evaluation of the newest generation Two-Probe Pitch tester, D&P ES4100-2, in three separate repeatability tests including right and left flanks resulted in a remarkable repeatability. The statistical evaluation of three separate tests with about 900 measurements each yielded one standard deviation of 0.06 to 0.08 microns. Even when applying the six sigma process variation model (that is con-
servative for precision instruments) the resulting six sigma pitch inspection repeatability variation is between 0.36 to 0.48 microns, see Figure 10.

SUMMARY
Gear pitch accuracy is one the most important characteristics affecting gear’s performance.

There are two fundamental methods for gear’s pitch inspection: single and two-probe. Both could provide accurate and repeatable results for a wide range of fine and medium pitch applications. However, when it comes to large gears, only the two-probe pitch inspection method provides consistent accuracy and repeatability regardless of the gear size.

The legacy two-probe pitch inspection methodology combined with modern computer and materials technologies, e.g. digital probes, wireless communication, and materials with a small coefficient of thermal expansion can yield remarkable repeatability — the six sigma repeatability variation below half a micron.

The two-probe pitch measuring method is most beneficial for large diameter gears. Most importantly, the inspection quality does not deteriorate with the increase of gear diameter. In addition, since the two-probe pitch inspection is a portable measuring unit, it can check large gears that are beyond the capacity of a traditional universal gear measuring machine. Lastly, the two-probe pitch inspection portability can sometimes reduce processing time and cost as it would not require moving the gear back and forth from cutting/grinding to an inspection machine.

BIBLIOGRAPHY

ABOUT THE AUTHORS
Yefim Kotlyar is the applications engineering manager at Machine Tool Builders (MTB), responsible for development of new gear manufacturing and gear metrology technologies. His broad experience in the art of gearing includes developments of various gear cutting and grinding technologies, analytical inspection, and evaluation technologies for gears and hobs, as well as gear systems design and validation. Kotlyar has served on a number of AGMA technical committees, and he has authored many articles on gearing subjects.

Christoph Donner is the CEO at Donner+Pfister AG, which has been in business for more than 30 years and is located at the upper reach of Lake Zurich in Switzerland. He earned the Dipl. Ing. (FH) degree in Zurich before starting his professional experience in the family-owned company more than 20 years ago. Donner leads the development and manufacturing of high precision gear grinding machines and high precision portable and stationary gear inspection machines, the development of specialized gear and hob inspection software, and servicing and re-controlling of legacy Maag gear grinding and inspection machines.