GEAR FUNDAMENTALS

Gear Fundamentals Reverse Engineering

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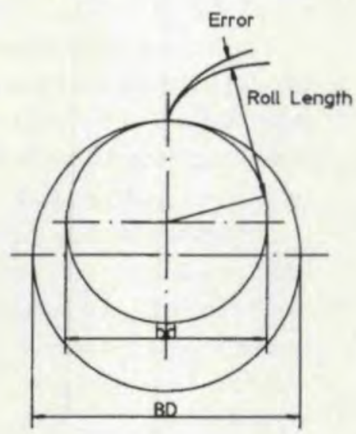
Introduction

Whether gear engineers have to replace an old gear which is worn out, find out what a gear's geometry is after heat treatment distortion, or just find out parameters of gears made by a competitor, sometimes they are challenged with a need to determine the geometry of unknown gears. Depending on the degree of accuracy required, a variety of techniques are available for determining the accuracy of an unknown gear. If a high degree of precision is important, a gear inspection device has to be used to verify the results. Frequently, several trial-and-error attempts are made before the results reach the degree of precision required.

The concept of the reverse engineering method described below is employed by some CNC gear measuring centers for automatic determination of unknown gear geometry. This article is an attempt to systematize a method for accurate determination of unknown gear geometry with or without the use of CNC inspection machinery and sophisticated software.



BD - Actual base circle diameter
bd - Assumed base circle diameter
Error - Involute error detected
Roll Length - Length of roll relevant to detected error

BD = bd * (1 + Error/Roll Length)

Fig. 1

Concept and Requirements

The result of a gear inspection provides enough information for determining actual gear geometry characteristics. For instance, the result of a gear involute inspection can be used for determining the actual base circle diameter (Fig. 1). The actual base circle diameter is a function of involute error, length of roll relevant to the involute error, and the base circle diameter which was assumed in order to conduct the involute inspection. Similarly, the results of a gear lead inspection provide sufficient data for calculating the actual lead (Fig. 2). Thus, by making an assumption for a gear base circle diameter and lead and using the results of the inspection based on this assumption, it is possible to determine the actual base circle and lead of an unknown gear.

Every gear has a unique base circle diameter and a unique lead. However, the same gear can have numerous combinations of Normal Pressure Angle (NPA), Normal Diametral Pitch (NDP), Pitch Diameter (PD), and Helix Angle (HA), because these parameters are relevant to gear mating qualities or cutting tools. Some gear drawings contain various combinations of NPA, NDP, PD, and HA. It is important to realize that only base circle and lead are unique and can be verified. The pitch diameter at which the gear is going to be meshed with another gear and related characteristics like NDP, NPA, and HA can only be guessed, since the same gear can mesh with various gears at different pitch diameters.

The main concept of this method is that the unique gear characteristics like base circle diameter and lead are indirectly measured first by trial-and-error technique with a specified degree of precision. One or several combinations of the rest of the parameters can be computed afterwards.

The task is divided into three steps. The first step is determining gear base circle diameter. The second step is determining lead - required only for helical gears. The third step is computing of other commonly used gear characteristics based on the base circle and lead.

The first and second steps require a lead and involute measuring machine with variable base circle setting capabilities. It does not have to be a modern CNC gear checker. However, utilizing a CNC gear checker, especially one which can follow the tooth form material, makes the determination of a gear's base circle and lead easier, more accurate, and requires fewer iterations.

Step 1 - Determination of Base Circle Diameter

Repeat Sub-steps 1.1 and 1.2 shown below until the slope error becomes smaller than the required gear accuracy. Generally, the accuracy does not have to be smaller than one micron (0.00004"). At any rate, it would be superfluous to use a number which is smaller than the accuracy limitation of the inspection machine. Because of imperfect gear surface conditions and possible inspection inaccuracies for gears with large errors, it is necessary to repeat Sub-steps 1.1 and 1.2, using a more and more accurate base circle diameter for each iteration.

The accuracy of the first assumption is not critical because every following iteration is a giant leap closer to the actual base circle diameter. Usually, no more than three iterations should be required, regardless of the first assumption. However, the base circle diameter assumption for the first iteration should be smaller or equal to the gear root diameter. Otherwise, since an involute does not exist below the base diameter, it might be impossible to make an involute inspection.

Sub-step 1.1. Assume a gear base circle (PBD) for the first iteration or use the result

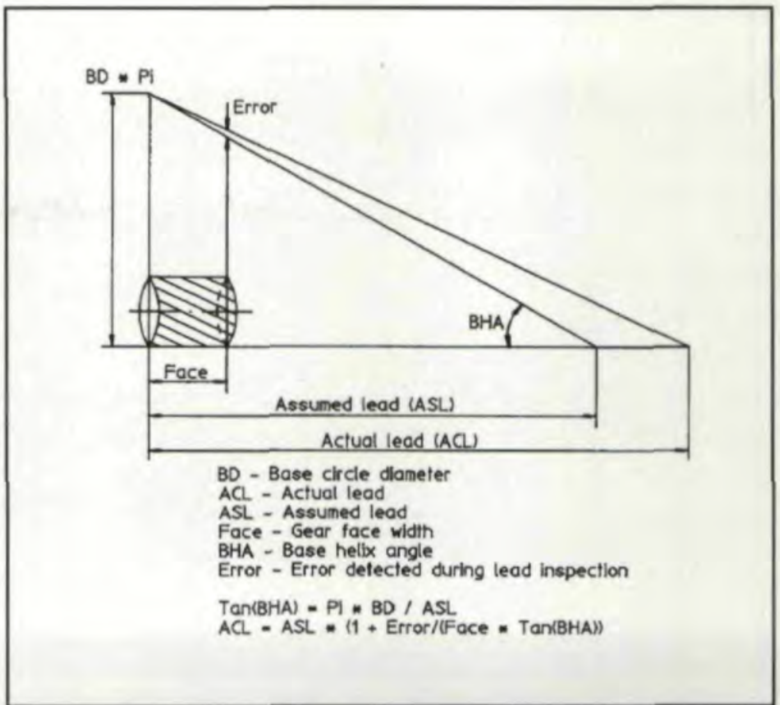


Fig. 2

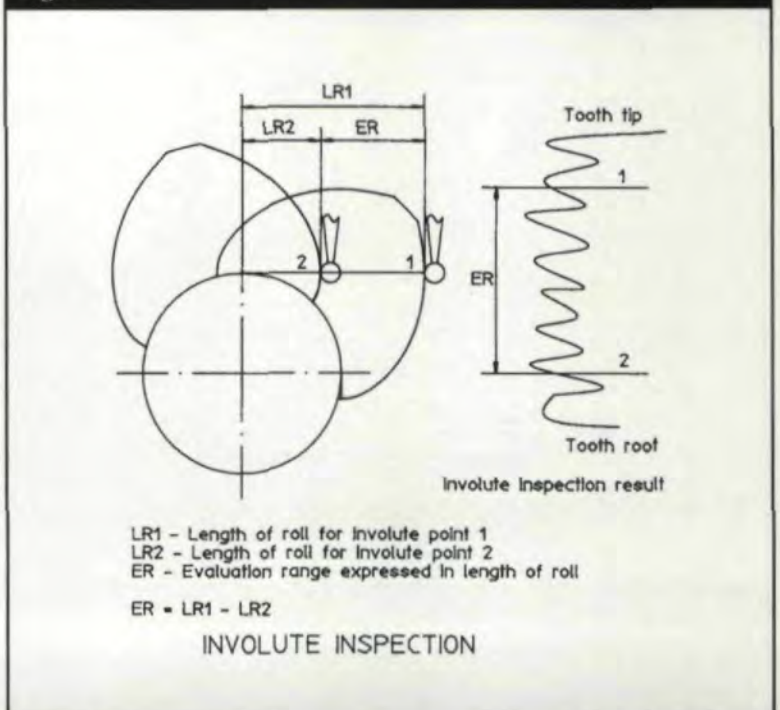


Fig. 3

calculated in Sub-step 1.2 for setting up an inspection machine. Inspect the gear involute and record slope error (Slope) and evaluation range (ER). The evaluation range is the length of roll for which slope error is observed (Fig. 3). Most inspection machines provide inspection results in a scale proportional to the length of roll, and this is the unit system that should be used. For instance, if the base circle diameter and evaluation range are in inches, then the slope error should be in inches as well. Depending on whether a material plus condition is closer to the root or tip

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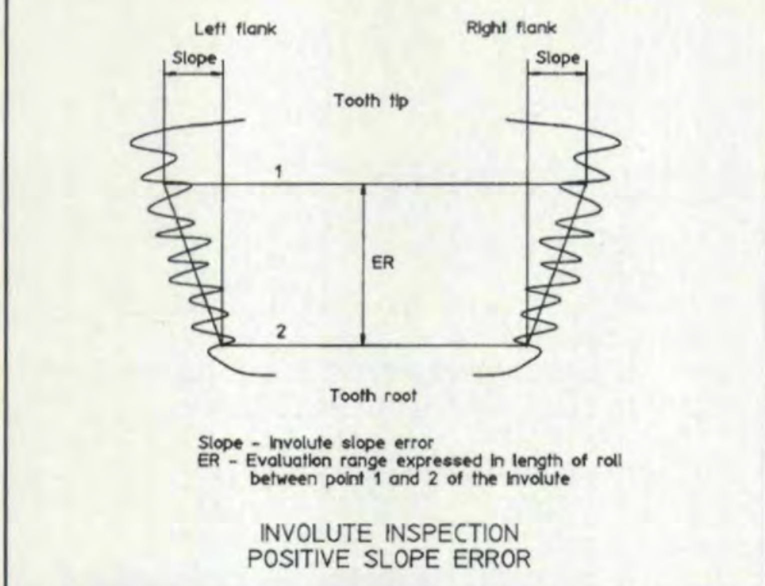


Fig. 4

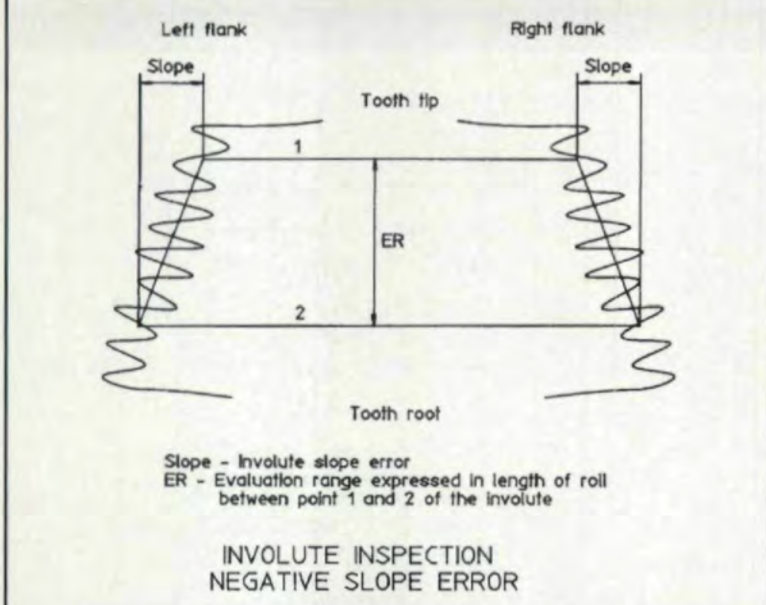


Fig. 5

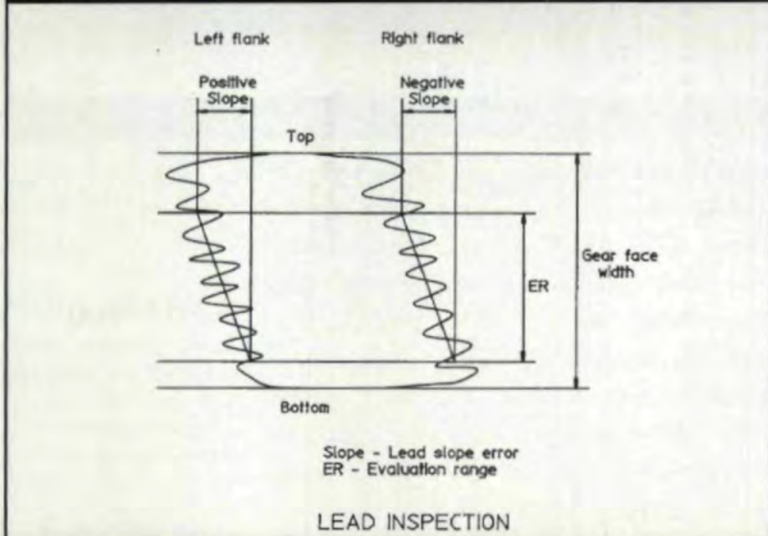


Fig. 6

of the tooth, the slope error should be positive or negative. (Figs. 4 and 5)

Sub-step 1.2. Determine a more accurate base circle diameter.

NBD = PBD * (1 + Slope/ER)

Where:

Slope = slope error recorded during inspection

ER = evaluation range

PBD = previous base demeter

NBD = new base diameter

If the slope error exceeds the required accuracy, Sub-steps 1.1 and 1.2 should be repeated using the new base circle diameter (NBD) for setting up an inspection machine.

Step 2 - Determination of Lead

(This step is not required when dealing with spur gears.)

As in Step 1, Sub-steps 2.1, and 2.2 should be repeated until the slope error becomes smaller then the required accuracy.

Sub-step 2.1. Assume a gear lead (for the first iteration) or use the result calculated in Sub-step 2.2 for setting up an inspection machine. Inspect the gear lead and record slope error (Slope) and evaluation range (ER).

The slope error is positive or negative, depending on whether a material plus condition exists on the inspected flank closer to the top or the bottom of the gear. (Fig. 6) Also note that some inspection machines require a different sign for lead depending on whether the right or left hand gear is checked.

Sub-Step 2.2. Determine a more accurate lead.

Tan (BHA) = Pi * BD / PL

NL = PL * (1 + (slope/ER)/Tan(BHA))

Where: BD = Base diameter determined in the Step 1

BHA = Base helix angle

ER = Evaluation range

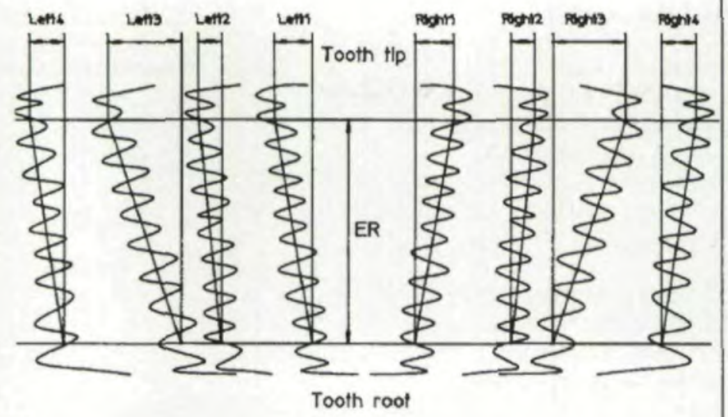
NL = New lead

PL = Previous lead

If the slope error exceeds the required accuracy, repeat Sub-steps 2.1 and 2.2 using a new lead (NL) for setting up an inspection machine.

Notes for Step 1 and Step 2

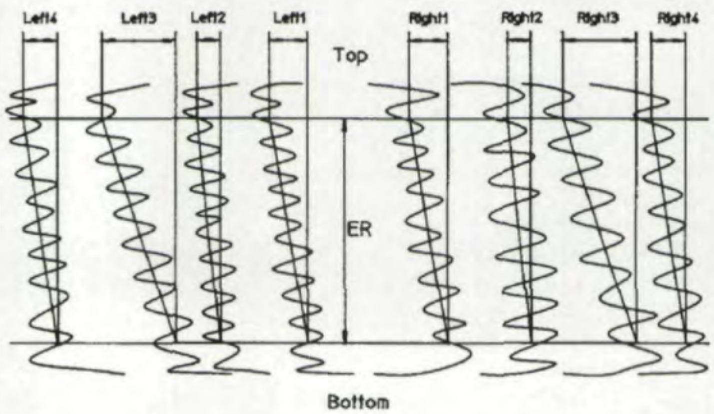
If the accuracy requirements are very high, then a more precise filtering out of the surface irregularities created by enveloping cuts or feed marks can be beneficial. In this case the assis-



Left Average = (Left1 + Left2 + Left3 + Left4) / 4
Right Average = (Right1 + Right2 + Right3 + Right4) / 4
Average Slope Error = (Left Average + Right Average) / 2

INVOLUTE AVERAGE SLOPE ERROR

Fig. 7



Left Average = (Left1 + Left2 + Left3 + Left4) / 4
Right Average = (Right1 + Right2 + Right3 + Right4) / 4
Average Slope Error = (Left Average - Right Average) / 2

LEAD AVERAGE SLOPE ERROR

Fig. 8

tance of a computerized "least square, best fit" slope calculation can be used.

The undesirable effects of gear run-out, wobble, and taper on the results can be decreased. Involute and lead slope errors can be averaged out by checking right and left flanks as well as several equally spaced teeth. (Figs. 7 and 8) The resulting average slope error can then be applied in the Steps 1.2 and 2.2. Obviously, this would prolong the inspection time, but would also provide more accurate results.

Since most inspection machines measure lead and involute in the transverse plane (plane of gear rotation), these formulae are valid for transverse plane inspection. If an inspection machine checks a gear in the normal plane, then the slope error in the transverse plane could be calculated approximately as follows:

Transverse slope error =
Normal slope error/Cos(Helix Angle)

Another difficulty may be encountered during gear inspection. Unless an inspection machine can follow the material, it is likely that the machine will run out of probe deflection range before completion of the profile or lead inspection. However, one

Assumed Parameter	Helical Gear	Calculated Parameters: Spur Gear
PD	HA = ArcTan (Pi * PD/Lead) NDP = Z/(PD * Cos(HA)) TPA = ArcCos (BD/PD) NPA = ArcTan (Tan(TPA) * Cos(HA)) BHA = ArcTan (Pi*BD/Lead)	NDP = Z/PD NPA = ArcCos (BD/PD)
HA	PD = Lead * Tan(HA)/Pi NDP = Z (PD * Cos(HA)) TPA = ArcCos (BD/PD) NPA = ArcTan (Tan(TPA) * Cos(HA)) BHA = ArcTan (Pi * BD/Lead)	
NPA	BHA = ArcTan (PI * BD/Lead) HA = ArcSin (Sin(BHA)/Cos(NPA) PD = Lead * Tan (HA)/Pi TPA = ArcCos (BD/PD) NDP = Z / (PD * Cos(HA))	PD = BD/ Cos (NPA) NDP = Z/PD
NDP	BHA = ArcTan (Pi * BD/Lead) HA = ArcSin (Z * Tan(BHA) (BD * NDP)) PD = Lead * Tan(HA)/Pi TPA = ArcCos (BD/PD) NPA = ArcTan (Tan(TPA) * Cos(HA))	PD = Z/NDP NPA = ArcCos (BD/PD)

Where: BD = Base Diameter determined in the Step 1
BHA = Base Helix Angle
HA = Helix Angle
Lead = Gear Lead determined in the Step 2
NPA = Normal Pressure Angle
PD = Pitch Diameter
Pi = 3.141592654
TPA = Transverse Pressure Angle
Z = Number of teeth

Table 1

(HA), and pitch diameter (PD) can be calculated. Since the same gear can have numerous combinations of these characteristics, one of them should be assumed in order to calculate the rest. Depending on whether pitch diameter, helix angle, normal pressure angle, or normal diametral pitch is assumed, one of the sets of formulae shown in Table 1 could be used in order to calculate other traditional gear characteristics.

Conclusions

The described technique assures accurate determination of a gear's actual base circle diameter and lead. Nevertheless, the results might slightly differ from the base circle and lead specified on the print because gears are manufactured imperfectly. If measuring machine inaccuracy is disregarded, the difference between the actual base circle and lead and a drawing specifications depends on how accurately the gear was manufactured.

It is also important to reiterate that various combinations of normal diametral pitch (NDP), normal pressure angle (NPA), helix angle (HA), and pitch diameter (PD) can be specified for the same gear. Thus, depending on need, selection of proper assumptions in Step 3 is important. Suppose one needs to reproduce an unknown gear and he has a stock of 20° pressure angle hobs. In such a case, it is reasonable in Step 3 to make an assumption for normal pressure angle of 20° and then calculate the rest, hoping that one of the available hobs could be utilized.