Programmable Separation of Runout From Profile and Lead Inspection Data for Gear Teeth With Arbitrary Modifications

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Abstract

A programmable algorithm is developed to separate out the effect of eccentricity (radial runout) from elemental gear inspection data, namely, profile and lead data. This algorithm can be coded in gear inspection software to detect the existence, the magnitude and the orientation of the eccentricity without making a separate runout check. A real example shows this algorithm produces good results.

Introduction

The effect of radial runout (or eccentricity) on the profile and lead deviations has been noticed for a long time. Gear engineers know that radial runout changes the slopes of the traces of profiles and leads. A normal gear inspection usually measures profiles and leads from three or more teeth, and the average is often taken to compensate for this effect. In 1993, Laskin *et al.* (Ref. 1) found the analytical equations which describe the interaction between these element measurements and the radial runout. The equations show the profile and lead traces of all teeth are segments of a sine curve if no profile and lead modifications are introduced. More recently, Laskin and Lawson (Ref. 2) developed the method to separate out the effect of runout from these elemental inspection data. They used linear or cubic fitting to get the slope of every elemental inspection curve. From the information given by the slopes, a sine curve is fit, and the effect of the runout represented by the sine curve is removed. The method does not apply to the case where arbitrary modifications exist, either on the profile or on the lead. However, the method works for partly modified profiles and leads, but the validity of the results is compromised because the fitting processes use only that portion of the profile (or the lead) that is free of modifications. If considerable roughness exists on the tooth surfaces, the curve fitting of these short trace segments is not very reliable.

This article presents a method that applies to any kind of modification of either profiles or leads. More importantly, only one fitting process that takes into consideration all the inspection data is used. The process is non-iterative, and a good result can be expected. This method only applies to gears with eccentricity (radial runout). It does not apply to egg-shaped gears or gears with considerable wobble (axial runout).

Extraction of Profile Modification from the Inspection Data

We start our discussion with profile inspection data. The same procedure applies to the lead inspection data. Referring to Fig. 1, the teeth and the base circles are plotted. Eq. 1 in Laskin *et al.* is cited here, and their symbols are used as well. The equation says:

$$M_{\phi L} = M_t M = e\sin(\angle EO_m N) = e\sin[(\theta_{e1M} - \alpha_{pBt}) + (k-1)\tau + \varepsilon_M] \quad (1)$$

where $\theta_{e1M}(\angle EO_m H)$ is the angle from the eccentricity direction to the center of Tooth 1. $\alpha_{pBt}(\angle B_o O_m H)$ is the angle extended by the half base tooth thickness. $\tau(2\pi/\text{teeth number})$ is the tooth pitch angle. $\varepsilon_M(\angle BO_m N)$ is the roll angle at the measurement point. e is the eccentricity.

If no profile modification exists, using Eq. 1 and Fig. 2, the profile trace f_p on each tooth is a segment of a sine curve having amplitude e. If an arbitrary profile modification $m_p(\varepsilon_M)$ is applied, the measured profile trace $(f_p + m_p)$ is the sinusoidal segment superimposed by the profile modification.

In real measurements, the inspection data may be presented separately or may be overlaid together and supplemented with a K chart. The final inspection data v_{pi} is $(f_p + m_p)$ shifted by D (referring to Fig. 2b, c).

$$v_{pi} = f_{pi} + m_p(\varepsilon_M) - D_i \quad i = 1, 2, \ldots, n. \quad (2)$$

n is the total number of measured teeth. $D_i(1,2, \ldots, n)$ are constants representing the shifts of profile traces, and they are unknown. Usually, three or four teeth are inspected, and n is either 3 or 4. From Eq. 1, the sinusoidal segment for the i^{th} measured profile trace is:

$$f_{pi} = e\sin[(\theta_{e1M} - \alpha_{pBt}) + (k_i - 1)\tau + \varepsilon_M] \quad i = 1,2,\ldots,n. \quad (3)$$

$k_i(i = 1,2,\ldots,n)$ are the tooth numbers. If we set:

$$\phi_i = (k_i - 1)\tau \quad i = 1,2,\ldots,n. \quad (4)$$

$$\varepsilon = (\theta_{e1M} - \alpha_{pBt}) + \varepsilon_M \quad (5)$$

These substitutions simplify Eq. 3 to:

$$f_{pi} = e \sin(\varepsilon + \phi_i) \quad i = 1,2,...,n. \tag{6}$$

Substituting Eq. 6 into Eq. 2 gives a new equation for the shifted profile traces.

$$v_{pi} = e \sin(\varepsilon + \phi_i) + m_p(\varepsilon_M) - D_i \quad i = 1,2,...,n. \tag{7}$$

Expanding and rewriting Eq. 7, we get:

$$e \sin(\varepsilon)\cos(\phi_i) + e \cos(\varepsilon)\sin(\phi_i) + m_p(\varepsilon_M) = v_{pi} + D_i \quad i = 1,2,...,n. \tag{8}$$

The profile modification m_p can be solved through any combination of three out of these n equations. If i_1^{th}, i_2^{th}, i_3^{th} equations are used, we have:

$$\left.\begin{aligned} e \sin(\varepsilon)\cos(\phi_{i1}) + e \cos(\varepsilon)\sin(\phi_{i1}) + m_p(\varepsilon_M) = v_{pi1} + D_{i1} \\ e \sin(\varepsilon)\cos(\phi_{i2}) + e \cos(\varepsilon)\sin(\phi_{i2}) + m_p(\varepsilon_M) = v_{pi2} + D_{i2} \\ e \sin(\varepsilon)\cos(\phi_{i3}) + e \cos(\varepsilon)\sin(\phi_{i3}) + m_p(\varepsilon_M) = v_{pi3} + D_{i3} \end{aligned}\right\} \tag{9}$$

Taking $e \sin(\varepsilon)$, $e \cos(\varepsilon)$ and $m_p(\varepsilon_M)$ as three unknowns, the mean profile modification, $m_p(\varepsilon_M)$, can be solved.

$$m_p = \frac{\begin{vmatrix} \cos(\phi_{i1}) & \sin(\phi_{i1}) & v_{pi1} \\ \cos(\phi_{i2}) & \sin(\phi_{i2}) & v_{pi2} \\ \cos(\phi_{i3}) & \sin(\phi_{i3}) & v_{pi3} \end{vmatrix} + \begin{vmatrix} \cos(\phi_{i1}) & \sin(\phi_{i1}) & D_{i1} \\ \cos(\phi_{i2}) & \sin(\phi_{i2}) & D_{i2} \\ \cos(\phi_{i3}) & \sin(\phi_{i3}) & D_{i3} \end{vmatrix}}{\begin{vmatrix} \cos(\phi_{i1}) & \sin(\phi_{i1}) & 1 \\ \cos(\phi_{i2}) & \sin(\phi_{i2}) & 1 \\ \cos(\phi_{i3}) & \sin(\phi_{i3}) & 1 \end{vmatrix}} \tag{10}$$

This solution depends on the reference of each profile which dictates the applied shifts, $D_i(i = 1,2,...,n)$. These shifts are unknown at this stage. But Eq. 10 reveals that the D_is only shift m_p upwards or downwards and do not change m_p's shape. Setting D_i to zero gives rise to:

$$m_p = \frac{\begin{vmatrix} \cos(\phi_{i1}) & \sin(\phi_{i1}) & v_{pi1} \\ \cos(\phi_{i2}) & \sin(\phi_{i2}) & v_{pi2} \\ \cos(\phi_{i3}) & \sin(\phi_{i3}) & v_{pi3} \end{vmatrix}}{\begin{vmatrix} \cos(\phi_{i1}) & \sin(\phi_{i1}) & 1 \\ \cos(\phi_{i2}) & \sin(\phi_{i2}) & 1 \\ \cos(\phi_{i3}) & \sin(\phi_{i3}) & 1 \end{vmatrix}} \tag{11}$$

Normalize m_p by making its maximum zero if necessary:

$$m_p - max(m_p) \Rightarrow m_p$$

If we want to make use of all of the inspection data to get a better result, all different combinations (i_1, i_2, i_3) out of $(i_1, i_2,...,i_n)$ can be used separately and the m_ps found can be averaged. In other words, if four profile traces are available, there are four combinations of these traces that could be used to get four mean profile traces that can be further averaged to give a global average.

The extracted profile modification m_p not only includes intended profile modifications, such as tip and root relief, but also includes some systematic profile error which shows the same tendency on each gear tooth. An example of a systematic profile error could be a pressure angle error (Ref. 4).

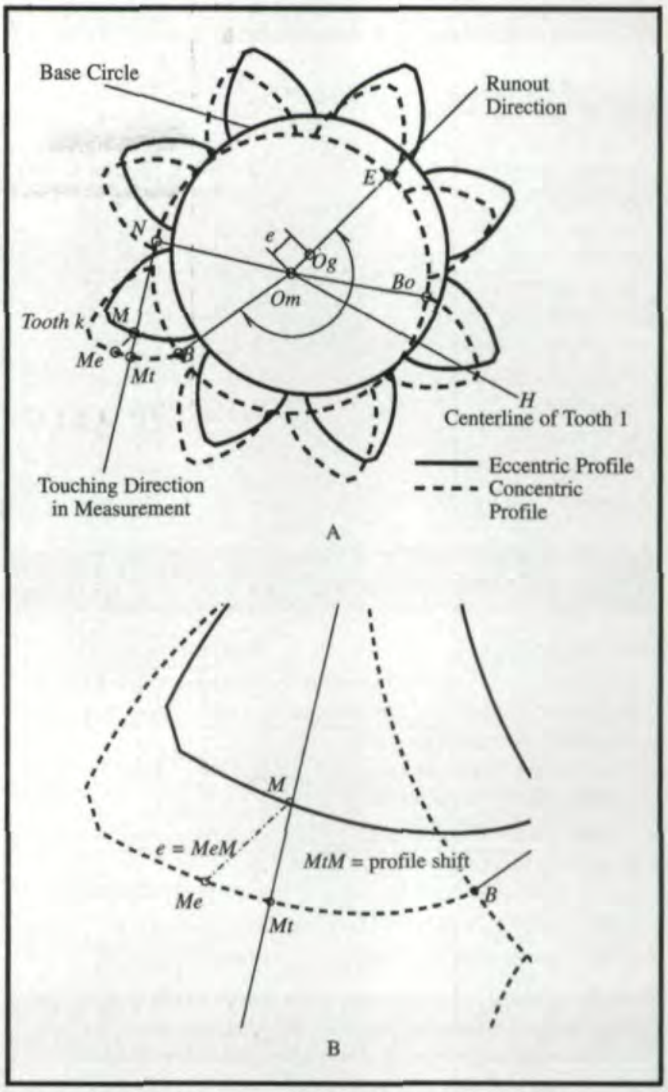


Fig. 1 – Profile Measurement on Eccentric Gear (left flank).

If the inspected teeth are exactly (in most cases, approximately) evenly spaced around the gear, the profile modification can be calculated simply by averaging the profile deviations measured on all inspected teeth. This practice is well known, and the proof is given here. Summarize Eq. 7 over $i = 1,2,...,n$.

$$\sum_{i=1}^{n} v_{pi} = e \sum_{i=1}^{n} \sin(\varepsilon + \phi_i) + n\, m_p(\varepsilon_M) - \sum_{i=1}^{n} Di$$

When the measured teeth are evenly distributed, $\sum_{i=1}^{n} \sin(\varepsilon + \phi_i)$ tends to disappear. Setting D_i to be zero shows that the average profile trace $m_p(\varepsilon_M)$ is a simple average of the individual profile traces.

$$m_p(\varepsilon_M) = \frac{\sum_{i=1}^{n} v_{pi}}{n} \tag{12}$$

Separation of Runout from Profile Inspection Data

After the modification is found, it can be removed from the individual profile traces, $v_{pi}(i = 1,2,...,n)$. The residuals, $v_{pi} - m_p(i = 1,2,...,n)$, caused by a pure eccentricity are the segments of a sine curve. A best fit is made to find the sine curve (both amplitude and phase) as shown in Eqs. 13–24.

Introducing new variable ε_1:

$$\varepsilon_1 = (\theta_{e1M} - \alpha_{pBt}) \tag{13}$$

TABLE 1 — GEAR GEOMETRY		
Parameter	Value	Unit
No. of Teeth	25	
Face Width	31.75	mm
Normal Pressure Angle	23.4541	degree
Helix Angle	21.5	degree
Normal Module	2.9541	mm
Normal Tooth Thickness	4.53	mm
Pitch Diameter	79.37	mm
Base Diameter	71.94	mm
Transverse Pressure Angle ϕ_{Mt}	25	degree
Transverse Tooth Thickness	4.87	mm
Helix Lead	633.05	mm
Helix Angle at Base Dia.	19.65	degree
Angle α_{pBt} in Eq. 1	5.23	degree
Angle α_{pMt} in Eq. 27	3.52	degree

TABLE 2 — BEST FIT RESULTS FROM PROFILE TRACES WITH ARTIFICIAL ECCENTRICITY		
Parameter	Value	Unit
Introduced Eccentricity Magnitude	0.0718	mm
Introduced Eccentricity Orientation	–118.77	degree
Magnitude e Found Out From Traces of Left Flanks	0.0693	mm
Orientation θ_{e1M} Found Out From Traces of Left Flanks	–120.31	degree
Magnitude e Found Out From Traces of Right Flanks	0.0746	mm
Orientation θ_{e1M} Found Out From Traces of Right Flanks	–122.48	degree

TABLE 3 – BEST FIT RESULTS FROM LEAD TRACES WITH ARTIFICIAL ECCENTRICITY		
Parameter	Value	Unit
Introduced Eccentricity Magnitude	0.0718	mm
Introduced Eccentricity Orientation	–127.8	degree
Magnitude e Found Out From Traces of Left Flanks	0.0588	mm
Orientation θ_{e1} Found Out From Traces of Left Flanks	128.66	degree
Magnitude e Found Out From Traces of Right Flanks	0.0462	mm
Orientation θ_{e1} Found Out From Traces of Right Flanks	128.24	degree

TABLE 4 – BEST FIT RESULTS FROM PROFILE TRACES WITHOUT ARTIFICIAL ECCENTRICITY		
Parameter	Value	Unit
Eccentricity Magnitude Detected by Runout Check	0.0105	mm
Eccentricity Orientation Detected by Runout Check	–164.2	degree
Magnitude e Found Out From Traces of Left Flanks	0.0101	mm
Orientation θ_{e1M} Found Out From Traces of Left Flanks	–174.34	degree
Magnitude e Found Out From Traces of Right Flanks	0.01014	mm
Orientation θ_{e1M} Found Out From Traces of Right Flanks	–146.5	degree

$$\varepsilon = \varepsilon_1 + \varepsilon_M \tag{14}$$

Eq. 7 becomes:

$$v_{pi} = e\sin(\varepsilon_1 + \varepsilon_M + \phi_i) + m_p(\varepsilon_M) - D_i \quad i = 1,2,\ldots,n. \tag{15}$$

We have $(n + 2)$ unknowns, $D_i(i = 1,2,\ldots,n)$, e and ε_1. Eqs. 15 are linearized by introducing:

$$D_{n+1} = e\sin(\varepsilon_1) \tag{16}$$

$$D_{n+2} = e\cos(\varepsilon_1) \tag{17}$$

Then,

$$f_i(\varepsilon_M) = -D_i + D_{n+1}\cos(\varepsilon_M + \phi_i) + D_{n+2}\sin(\varepsilon_M + \phi_i) + m_p(\varepsilon_M) - v_{pi} = 0 \quad i = 1,2,\ldots,n. \tag{18}$$

If p points are measured on each flank, then totally p x n equations exist. We will solve all p x n equations by minimizing F, where

$$F = \sum_{j=1}^{p}\left(\sum_{i=1}^{n} f_i^2(\varepsilon_{Mj})\right) \tag{19}$$

$\varepsilon_{Mj}(j = 1,2,\ldots,p)$ are the roll angles corresponding to the measured points. Setting $\frac{\partial F}{\partial D_k}$ $(k = 1,\ldots,n + 2)$ to zero gives $(n + 2)$ linear equations:

$$[A]_{(n+2)\mathrm{x}(n+2)}[D]_{(n+2)\mathrm{x}1} = [B]_{(n+2)\mathrm{x}1} \tag{20}$$

where,

$$a_{ij} = \begin{cases} p & i = j \\ 0 & i \neq j \end{cases} \qquad i, j = 1,2,\ldots,n.$$

$$a_{n+1,i} = a_{i,n+1} = -\sum_{j=1}^{p}\cos(\varepsilon_{Mj} + \phi_i) \quad i = 1,2,\ldots,n$$

$$a_{n+2,i} = a_{i,n+2} = -\sum_{j=1}^{p}\sin(\varepsilon_{Mj} + \phi_i) \quad i = 1,2,\ldots,n$$

$$a_{n+1,n+1} = \sum_{j=1}^{p}\sum_{i=1}^{n}\cos^2(\varepsilon_{Mj} + \phi_i)$$

$$a_{n+1,n+2} = a_{n+2,n+1} = \sum_{j=1}^{p}\sum_{i=1}^{n}\sin(\varepsilon_{Mj} + \phi_i)\cos(\varepsilon_{Mj} + \phi_i)$$

$$a_{n+2,n+2} = \sum_{j=1}^{p}\sum_{i=1}^{n}\sin^2(\varepsilon_{Mj} + \phi_i)$$

$$b_i = -\sum_{j=1}^{p}[v_{pi}(j) - m(\varepsilon_{Mj})] \quad i = 1,2,\ldots,n$$

$$b_{n+1} = \sum_{j=1}^{p}\sum_{i=1}^{n}[v_{pi}(j) - m(\varepsilon_{Mj})]\cos(\varepsilon_{Mj} + \phi_i)$$

$$b_{n+2} = \sum_{j=1}^{p}\sum_{i=1}^{n}[v_{pi}(j) - m(\varepsilon_{Mj})]\sin(\varepsilon_{Mj} + \phi_i)$$

The solution is:

$$[D] = [A]^{-1}[B] \tag{21}$$

$$\text{eccentricity magnitude } e = \sqrt{D_{n+1}^2 + D_{n+2}^2} \tag{22}$$

$$\varepsilon_1 = \arctan\left(\frac{D_{n+1}}{D_{n+2}}\right) \tag{23}$$

$$\text{eccentricity location} \quad \theta_{e1M} = \varepsilon_1 + \alpha_{pBt} \tag{24}$$

The system of Eq. 20 can be very efficiently solved using the Gaussian Elimination Method (Ref. 3). It is not necessary to invert the coefficient matrix A. The profile deviations after the removal of the effect of runout are:

$$\overline{v_{pi}} = v_{pi} + D_i - e\sin(\varepsilon_1 + \varepsilon_M + \phi_i) \quad i = 1,2,...,n. \tag{25}$$

For the right flank, Eq. 4 in Laskin *et al.* (Ref.1) says:

$$M_{\phi R} = e\sin[-(\theta_{e1M} + \alpha_{pBt}) - (k-1)\tau + \varepsilon_M] \tag{26}$$

Similar steps can be followed to obtain the magnitude and orientation of the eccentricity from the profile traces of the right flanks.

Separation of Runout from Lead Inspection Data

For spur gears, runout does not affect the lead inspection data. The separation is applicable only for helical gears. Referring to Fig. 6 in Laskin *et al.* (Ref. 1), Eq. (13) of the sinusoidal curve of lead traces says:

$$M\psi_L = e\cos(\psi_b)\sin[\theta_{e1} + (\phi_{Mt} - \alpha_{pMt}) + (k-1)\tau + x_M \frac{2\pi}{L}] \tag{27}$$

where ψ_b is the base helix angle. θ_{e1} is the angle from the eccentricity direction to the center of tooth 1 at the top face. ϕ_{Mt} is the transverse pressure angle at the measurement diameter. α_{pMt} is the angle extended by the half tooth thickness at the measurement diameter. L is the helix lead (negative for left handed gears). x_M is the axial distance from the top face to the measurement point.

Eq. 27 has the same format as Eq. 1. We first define:

$$e_l = e\cos(\psi_b) \tag{28}$$

$$\varepsilon_1 = \theta_{e1} + (\phi_{Mt} - \alpha_{pMt}) \tag{29}$$

$$\varepsilon_M = x_M \frac{2\pi}{L} \tag{30}$$

$$\varepsilon = \varepsilon_1 + \varepsilon_M \tag{31}$$

From Eqs. 27–31, the lead trace f_l due to the eccentricity can be expressed as:

$$f_{li} = e_l \sin(\varepsilon + \phi_i) \quad i = 1,2,...,n. \tag{32}$$

If an arbitrary lead modification m_l is applied, the measured lead deviations can be written as:

$$v_{li} = e_l \sin(\varepsilon + \phi_i) + m_l(\varepsilon_M) - D_i \quad i = 1,2,...,n. \tag{33}$$

The mean lead modification m_l can be expressed by the ratio of two determinants.

$$m_l = \frac{\begin{vmatrix} \cos(\phi_{l1}) & \sin(\phi_{l1}) & v_{ll1} \\ \cos(\phi_{l2}) & \sin(\phi_{l2}) & v_{ll2} \\ \cos(\phi_{l3}) & \sin(\phi_{l3}) & v_{ll3} \end{vmatrix}}{\begin{vmatrix} \cos(\phi_{l1}) & \sin(\phi_{l1}) & 1 \\ \cos(\phi_{l2}) & \sin(\phi_{l2}) & 1 \\ \cos(\phi_{l3}) & \sin(\phi_{l3}) & 1 \end{vmatrix}} \tag{34}$$

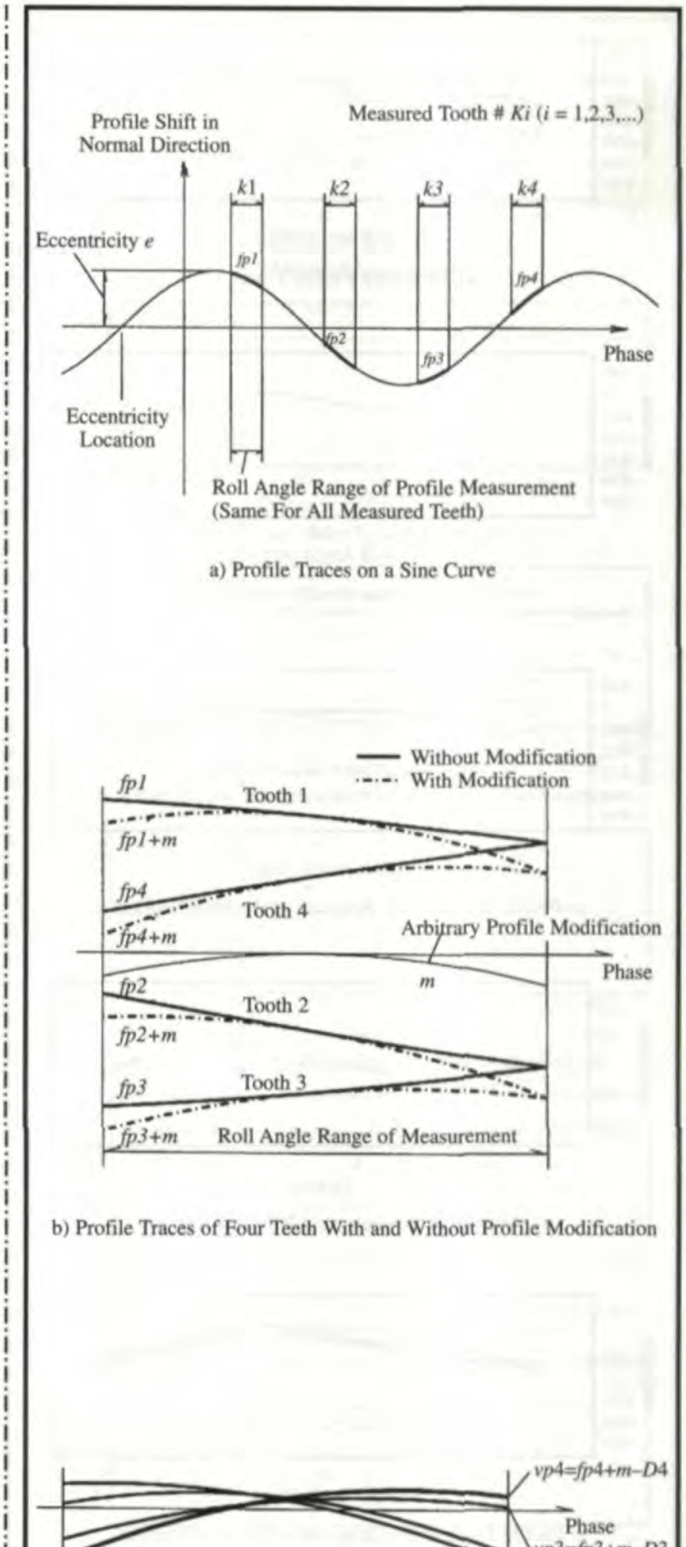
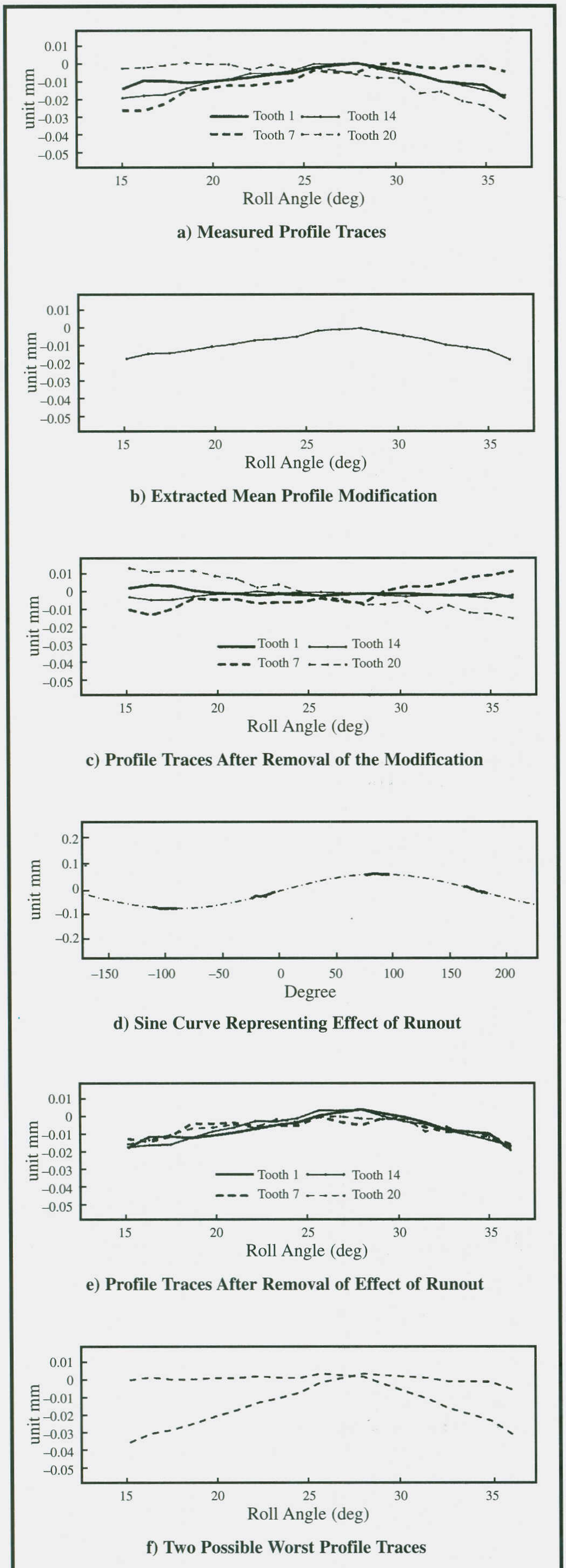


Fig. 2 – Profile Measurements with Arbitrary Modification.



a) Measured Profile Traces

b) Extracted Mean Profile Modification

c) Profile Traces After Removal of the Modification

d) Sine Curve Representing Effect of Runout

e) Profile Traces After Removal of Effect of Runout

f) Two Possible Worst Profile Traces

Fig. 3 – Example Gear Inspection: 4 teeth inspected; left flank; profile trace.

where ϕ_i, $D_i(i = 1,2,...,n)$ have the same meanings as in Eq. 10.

The extracted mean lead modification, m_l, not only includes the intended lead modification, such as crowning, but also includes the systematic lead error which shows the same tendency on each gear tooth. An example of such a systematic lead error could be the alignment error (Ref. 4).

Similarly, if the inspected teeth are exactly (in most cases, approximately) evenly spaced around the gear, the mean lead modification can be calculated simply by averaging the individual lead traces measured on all inspected teeth.

Using Eqs. 31 and 33:

$$v_{li} = e_l \sin(\varepsilon_l + \varepsilon_M + \phi_i) + m_l(\varepsilon_M) - D_i \quad i = 1,2,...n. \tag{35}$$

Eq. 35 has the same format as Eq. 15. Solution of Eqs. 19–21 could be used, but $v_{li}(i = 1,2,...,n)$ should be used instead of $v_{pi}(i = 1,2,...,n)$, while $b_k(k = 1,2,...,n + 2)$ in Eq. 20 are calculated. e_l and ε_1 are obtained,

$$e_l = \sqrt{D_{n+1}^2 + D_{n+2}^2} \tag{36}$$

$$\varepsilon_1 = \arctan\left(\frac{D_{n+1}}{D_{n+2}}\right) \tag{37}$$

The amplitude and the phase of the sine curve from the eccentricity are:

eccentricity magnitude $\quad e = e_l/\cos(\psi_b)$ (38)

eccentricity location $\quad \theta_{el} = \varepsilon_1 - (\phi_{Mt} - \alpha_{pMt})$ (39)

Example Inspection of A Real Helical Gear

A Boeing NASA helical gear was inspected to verify the developed algorithm. The geometry of the gear is listed in Table 1. Originally the gear had very little eccentricity, so an artificial eccentricity of 0.0718 mm was created on the CMM (Coordinate Measurement Machine). Four teeth were inspected by a universal CMM. The CMM has a resolution of one micron, and an accuracy of about three microns. According to the specification, a circular profile modification was applied from the form diameter to the outside diameter. No lead modification was required. The profile inspection was performed at the middle of the face width, and the lead inspection was performed at the pitch diameter.

Fig. 3 shows the profile inspection data. Only the traces of the left flanks are given here. The original deviation curves are drawn in Fig. 3a. The extracted mean profile modification is presented in Fig. 3b. The profile traces after the removal of the modification are shown in Fig. 3c. The fitted sine curve is shown in Fig. 3d. The profile traces after the removal of the effect of runout are shown in Fig. 3e. The maximum and minimum slopes of the fitted sine curve is its amplitude e and $-e$ respectively. If these slopes are added to the mean profile trace m_p, we can get the two possible worst profile traces that could be obtained in profile inspection. These two possible worst profile traces are shown in Fig. 3f. The results of the best fit are listed in Table 2.

Fig. 4 shows the lead inspection data. No lead modification appears to exist on the gear. The results are presented in Fig. 4a–4f and Table 3 respectively. Note that the orientation angles of the introduced eccentricity are different in Table 2 and Table 3 because the first one is relative to the centerline of Tooth 1 at the middle of the face width where profile measurements were performed, and the second one is relative to the centerline of Tooth 1 at the top face as stated in Eq. 27.

Conclusions and Comments

A new programmable algorithm is developed to separate out the effect of runout from the profile and lead inspection data. The method presented here is more convenient, more reliable and easier to program than that proposed by Laskin and Lawson (Ref. 2). Because the pure radial runout does not contribute to the noise and vibration of transmissions as much as the real profile and lead deviations (Ref. 2), the separation of the effect of runout from profile and lead inspection data is significant.

In the Gear Dynamics and Gear Noise Research Laboratory at The Ohio State University, a CMM is often used to inspect gears. The effect of runout was removed using a two-step inspection, where runout inspection was performed, a new center was determined; profile and lead inspections were performed based on the new center. This approach takes more time. The approach presented in this paper gives us an alternative way to save inspection time.

In our example, the fitting process from the profile inspection data produces a better result than the fitting process from the lead inspection data. It is expected because a regular gear with non-negligible wobble (axial runout) is used instead of a test gear of very good accuracy as in Laskin and Lawson (Ref.2). In most cases, the profile traces are preferred in the separation of the effect of runout, particularly when the face width of a gear is relatively small compared with its helix lead. In this case, the lead traces are tiny segments (Fig. 4d) of the sine curve, and this makes the fitting process less reliable. Compared with Fig. 3d, the profile traces are longer than the lead traces for our test gear (1.5:1). The use of lead inspection data to separate out the effect of runout should be avoided unless the helix angle and/or the face width are really large.

The same gear was inspected once more. This time no artificial eccentricity was introduced. Its actual eccentricity was detected through a separate runout check. The eccentricity was also calculated from the profile traces. The results were listed in Table 4.

The separation of eccentricity based on the profile traces was very successful, but the separation of eccentricity based on the lead traces failed in this case. The reason is the gear has wobble (axial runout) comparable with the eccentricity (radial runout) that violates the wobble-free assumption from which Eq. 27 was derived.

A more ambitious approach would be to use all the inspection data from both flanks to make one sine curve fitting. Take the profile inspection data as example. The sine curves represented by Eq. 26 (for right flank) and Eq. 1 (for left flank) can be viewed as the same sine curve (the phase difference can be calculated). We could then fit the profile traces of both left and right flanks to one single sine curve. This approach has not been tried yet by the authors.

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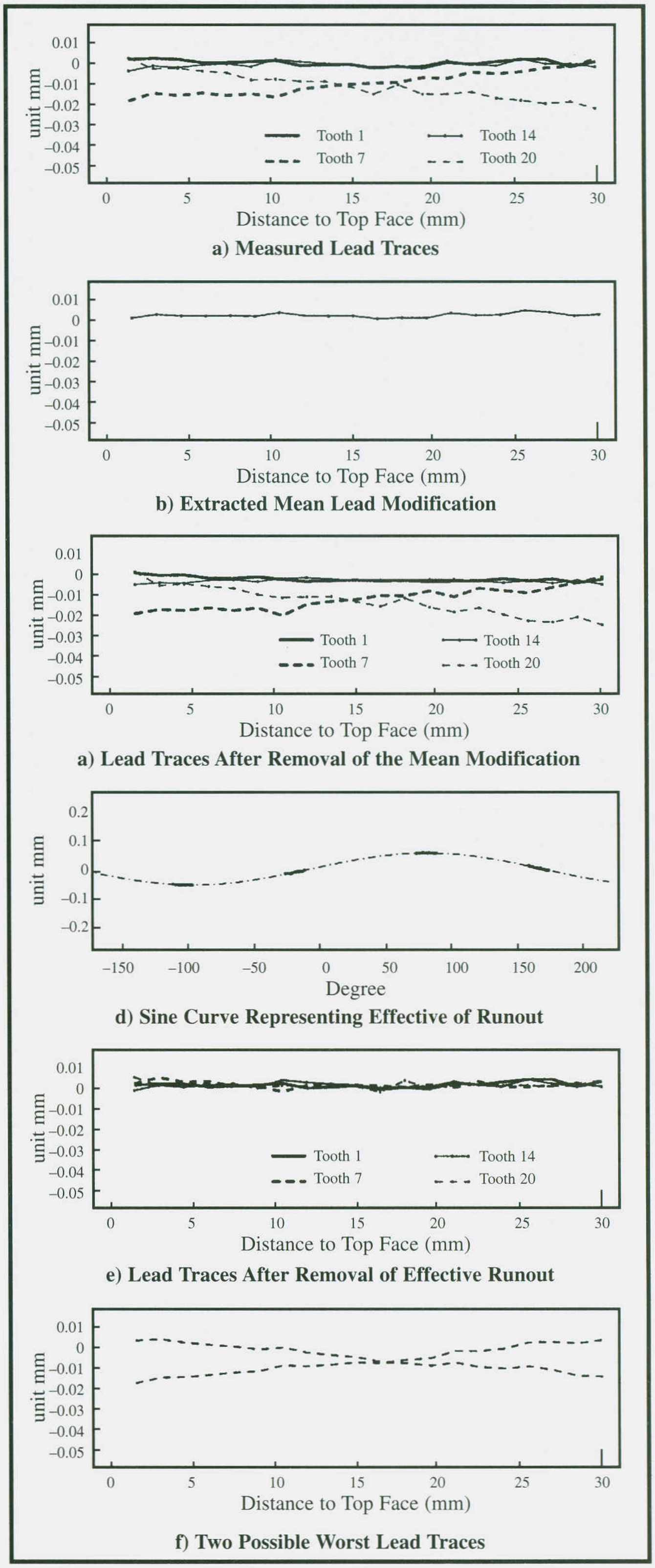

a) Measured Lead Traces

b) Extracted Mean Lead Modification

a) Lead Traces After Removal of the Mean Modification

d) Sine Curve Representing Effective of Runout

e) Lead Traces After Removal of Effective Runout

f) Two Possible Worst Lead Traces

Fig. 4 – Example Gear Inspection: 4 teeth inspected; left flank; lead trace.

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