Easy set-up and in situ automatic gear diagnostic system using only laser reflection

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Abstract
We developed a new method that can diagnose damage on a gear tooth surface using a laser beam without a rotary encoder. The method procedure is as follows: 1) The tooth bottom, the tooth tip and their two median values are detected using the differential values of the laser reflection data. 2) The gear rotation speed is calculated with these four positions, and interpolated according to the rotation fluctuation. 3) Using the calculated gear rotation speed, the measured data can be converted to the corresponding gear rotation angles. Thus we can diagnose the damage of the gear tooth surface precisely and can easily set up the experimental measurements without being influenced by rotational fluctuation. To confirm the validity of the method, we conducted the diagnosis experiment and we created contour maps to show the diagnosis accuracy variation according to the fluctuations of the amplitude and cycle. Based on these maps, we found that the diagnosis accuracy of the damage size is the same irrespective of the presence or absence of a rotary encoder. The diagnosis accuracy of the damage location without using a rotary encoder is lower than the result obtained using a rotary encoder because we assumed that the detection of the damage start point is delayed using this new method. Furthermore, we defined the limit using the conditions of this method from the sampling theorem; the validity of this definition could also be confirmed from the contour map.

Key words: Gear, Damage diagnosis, Laser reflection, Rotational fluctuation

1. Introduction
Industrial machine maintenance requirements have created a demand for the development of remote diagnostic systems for gear teeth. Several maintenance methods for the diagnosis of damage to gear-teeth surfaces have already been developed using different techniques such as acoustic emission (Toutountzakis and Mba, 2003) (Miyachika, et al., 2006) and vibration (Haloui, et al., 2007) (Diwakar, et al., 2012) (Ohue, et al., 2011). However, it is still difficult to identify the location of the damage and provide a detailed estimate of its scale. To solve this problem, we developed a method that uses a laser beam for remote diagnosis (Tanaka, et al., 2011) and verified this method can diagnose gear tooth surface abnormalities on a lubricated gear in a practical gearbox. We also developed a real-time pit-detection
algorithm to create an automated gear-tooth diagnosis system (Tanaka, et al., 2011). Our method compares the measured laser reflection data and previous damage data or the mean data of all measured teeth. However, in some cases, it may be difficult to measure the initial data prior to damage. Furthermore, if all teeth are damaged at almost identical locations on each tooth surface, the damaged shape is perceived to be normal in this method. To solve these issues, we suggested a novel diagnosis method to predict the previous damaged laser reflection data and compare the measured data (Tanaka, et al., 2013a). However, the above mentioned laser diagnostic system requires a rotary encoder in order to obtain angle values of the targeted gear shaft during the laser measurement; this presents a problem because it is difficult to attach the rotary encoder on a gear shaft of gearboxes used in some factories. We then we developed a new diagnostic method without a rotary encoder for easy on-site diagnosis of the gear tooth surface condition (Tanaka, et al., 2014) (Nakajima, et al., 2015). This method is as follows: 1) the tooth bottom, the tooth tip and their two medians are detected using the differentials of the laser reflection data. 2) The gear rotation speed is calculated from these four positions and a spline interpolation function is calculated to derive the rotational fluctuation. 3) The calculated gear rotation speed is used to convert the measured data to the data corresponding to the gear rotation angle. In this study, we confirm the validity of our method using the comparison between the experimental results obtained for the contour maps of diagnosis accuracy using this method and those obtained using a rotary encoder. Furthermore, we defined the limit of applicability using the conditions of this method from the sampling theorem; the validity of this definition could be also confirmed from the examination of the contour map.

2. Nomenclature

\( l_{\text{laser}} \): Length of the sensor to the irradiated point on the tooth surface [mm]
\( l \): Length of tooth tip to base circle on gear surface, \( l = r_0 \tan \theta \left( \cos \alpha \left( r_b / r_0 \right) \right) / 2 \) [mm]
\( l_1 \): Length between base circle and the lower edge of the damage point on the tooth surface [mm]
\( l_2 \): Length between base circle and the upper edge of the damage point on the tooth surface [mm]
\( l_3 \): Length between the upper edge of the damage point and the semi topping on the tooth surface [mm]
\( l_4 \): Length of the semi topping of the tooth surface direction [mm]
\( l_5 \): Length of the semi topping [mm]
\( m \): Module [mm]
\( n_r \): Number of sampling points
\( r \): Radius of the circle able to define the laser beam as the tangential line [mm]
\( r_0 \): Radius of the pitch circle, \( r_0 = m z/2 \) [mm]
\( r_0' \): Radius of the tip circle, \( r_0' = m z/2 + m \) [mm]
\( r_b \): Radius of the base circle, \( r_b = m z(\cos \alpha)/2 \) [mm]
\( T_l \): Cycle of gear rotational fluctuation [s]
\( t_s \): Sampling period of laser measurement [s]
\( x_1 \): Length of the damaged range on the tooth surface
\( x_2 \): Length of the center of the damaged range to tooth tip on the tooth surface [mm]
\( z \): Number of teeth
\( \alpha \): Reference pressure angle [rad]
\( \omega_0 \): Gear rotation speed during laser measurements [rad/s]
\( \theta_1 \): Angle of gear rotating shaft [rad]
\( \theta \): Angle of gear rotating corresponding to \( l \)
\( \theta_1 \): Angle of gear rotating corresponding to \( l_1 \)
\( \theta_2 \): Angle of gear rotating corresponding to \( x_1 \)
\( \theta_3 \): Angle of gear rotating corresponding to \( x_2 \)

3. Laser-Scattering Damage Diagnosis Method and Automated Gear Tooth Diagnosis System

Our method is illustrated in Fig. 1. First, a gear-tooth surface is irradiated at an oblique angle by a linear laser beam, as shown in Fig. 1(a). As the gear rotates, the entire circumference of the gear is irradiated by the laser, as shown in Fig. 1(b). The laser reflects both specularly and diffusely from the gear-tooth surface, and as the pitting on the
surface increases, the diffuse reflection (i.e., scattering) increases at the expense of the specular reflection. The optical detector detects a portion of the scattered laser light and converts it into a proportional voltage that is read out in real time (i.e., as the gear is rotating). The location of the damage on the tooth surface may be derived from the angle of the gear rotating axis, \( \theta_g \), i.e., the angle through which the gear rotates to reach an arbitrary point \( P_0 \) on the gear tooth from the point where the laser beam irradiates the base circle (see Fig. 2), may be defined as follows:

\[
\theta_g = \theta_1 + \theta_2 = \arctan(\cos^{-1}(r_\beta/R)) + \cos^{-1}(r_\beta/R) - \cos^{-1}(r_\beta r_1).
\]

When a damaged point on the gear-tooth surface is detected, the value of \( \theta_g \) for this point can be determined from the laser-scattering data. Once \( \theta_g \) is known from the rotary encoder data, \( R \) can be calculated according to Eq. (1). Using the obtained \( R \) values, the damaged point on the gear-tooth surface can be expressed as a distance \( l_{\text{laser}} \) from the base circle:

\[
l_{\text{laser}} = r_b \tan^2(\cos^{-1}(r_\beta /R)) / 2.
\]

In Fig. 2, the distance between the laser sensor and tooth profile curve of the targeted gear is defined as \( l_{\text{laser}} \), the irradiation angle is \( \theta_1 \), and the irradiated point is \( P_0(x_0, y_0) \). By comparing the initial and current laser-scattering data, we can estimate the tooth-surface conditions and detect damages such as initial or abnormal abrasion, pitting, and spalling.

The influence of the variations of the laser beam distance and the angle was taken into account and the method was described in a previous paper (Tanaka, et al., 2007). The laser irradiation angle conditions can be defined, as discussed in a previous paper (Tanaka, et al., 2013b). The hardware configuration of the automated gear-tooth diagnosis system and the control system are also described explained in previous publications (Tanaka, et al., 2014) (Nakajima, et al., 2015). Therefore, in this study, we focus our discussion mainly on our new method that can determine angle \( \theta_g \), as shown in Fig. 2, without a rotary encoder.

![Image](image_url)
4. Three Step Damage Diagnosis Method

We developed the three-step remote automatic diagnostic method as shown in Fig. 3. The method is as follows:

1. First step: if the measured reflection voltage data for all teeth of the targeted gear were already measured prior to use (Data A), these data are defined as the benchmark (normal data) for each tooth.

2. Second step: if the targeted gear was not measured previously and only a few teeth are partially damaged on the entire gear, the results of the current measurements may be taken as Data B, as shown in Fig. 3 (abnormal area data are shown with red lines). Then, the measured mean tooth data of all teeth (Data C) can be constructed and defined as the benchmark for all teeth.

3. Third step: if the targeted gear was not measured previously and almost all teeth are damaged, the current measured result is taken as Data B', as shown in Fig 3, and it is difficult to construct the benchmark from the measured data. Therefore, the laser reflection data are predicted according to various gear specifications using the angle-distance relation map created from pre-measured data of the same material and heat treatment, and taking into account the influence of the adjacent teeth (Tanaka, et al., 2013a). To construct the diagnosis benchmark, three dimensional basic-data map (x: irradiated angle, y: irradiated distance, z: reflection intensity) was created by measuring the gear for which the material, heat treatment, and roughness were the same as those of the targeted gear. Using the equations of the tooth profile and the fillet curves calculated from the specifications of the targeted gear, the distance and angle relations between the laser sensor and the tooth surface can be derived. Then, the benchmark can be created using the three dimensional basic-data map.

4. Finally, we subtracted the benchmark from the current measured data that was scanned using a two-step thresholds computer program. If the value of the data was higher than the thresholds, the area was defined as a damaged area and location.

This computer program could detect the damaged locations. However, the accuracy of the range of the area was not satisfactory. To improve the accuracy for determining the pit length, it is important to properly define the threshold voltage.

However, in this three-step damage diagnosis method, the measured data B or data B’ must correspond to the gear rotation angle. The next section describes the new method for obtaining the gear rotation angles from the measured data.
Fig. 3 Three step diagnosis method

5. Method of Removing Effects of Rotational Fluctuation without a Rotary Encoder
5.1 Effects of Rotational Fluctuation in Case of Horizontal Axis Converting

The laser measuring device provides the voltage data that is proportional to the received laser reflection as shown in Fig. 4. The voltage during measurements from a pitch point to a tooth tip is comparatively high, whereas the voltage is low during measurements the nearby boundary of a tooth surface and tooth space. This is due to the laser irradiation angle and the irradiation distance. If some damage is present on the tooth surface, voltage spikes appear in the laser measured data. The laser measured data for one tooth in the two cases of gear shaft rotation are shown in Figs. 5A and 5B (the numbers of samplings are minimized for visibility). The horizontal axes represent time (number of samples) because the sampling points have even intervals originating from the laser measurement sampling period. Laser measurements with a constant gear rotating speed give rise to the regular shape as found in the case of data C (Horizontal: gear rotation angle, Vertical: voltage); therefore, data A are comparable with the benchmark data for the damage diagnosis. Data B show the effects of increasing the gear rotation speed during laser measurements. The shape of data B is obviously different from that of data A; therefore, data B cannot be compared with the benchmark data.

If we use a rotary encoder attached to the rotation shaft of the targeted gear, the horizontal axes of data A and B are easily interchangeable with the gear rotation angle, and data A and B can then be converted to data C and D. Comparison of the data C and D to the benchmark data makes it easy to identify the location of the damage on the tooth.
surface from the gear rotation angle data. However, if we use this diagnosis system on some reduction gears that are being used in practical factories, it is difficult to attach a rotary encoder to the targeted gear rotating shaft. Therefore, to solve this problem, data B must be converted to data D without a rotary encoder. The next section explains the method for the conversion without a rotary encoder.

![Graph](image)

**Fig. 4 Example of detailed laser measured data for one tooth**

![Graph](image)

**Fig. 5 Laser measured data of one tooth in several cases**
5.2 Details of the converting method

We developed the method for converting data B to data D (shown in Fig. 5) by calculating the gear rotating speed. First, we calculate the derivative values of the laser measured data and identify two positions where the curve crosses zero, as shown in Fig. 6(1). Second, we identify two median data between the nearly tooth tip positions and the nearly tooth bottom positions from the laser measured data as shown in Fig. 6(2). Third, we count the numbers of sampling points \( n_i \) between each of the identified points (e.g., the number from the nearly tooth bottom \( \Delta \) to the neighbor nearly tooth bottom \( \Delta \)), as shown in Fig. 6(3). For example, when we focus on the marked points (\( \Delta \)), the numbers of sampling points between the marked points are counted. This counting rule is also followed for the other marked points. On substituting the counted numbers of sampling points for \( n_i \) in Eq. (3), the gear rotation speed values are derived, as well as the average values between the two positions for which the sampling points are counted.

\[
\omega_m [\text{rad/s}] = \frac{\theta_d}{t_s} = \frac{2\pi}{(n_i z)}. \tag{3}
\]

However, the calculated gear rotation speed values are discrete so we convert the discrete values to continuous values using cubic spline interpolation, as shown in Fig. 6 (4). In addition, gear rotation angles can be obtained for each sample of the measured data using the integrated values of the cubic spline interpolated results. Therefore, the horizontal axis of the data can be converted to represent the gear rotation angle. This means that the measured data can be normalized for diagnosis.
Fig. 6 Method for calculating gear rotation speed from laser measured data

1. Calculate derivative values of the laser measured data
2. Detect tooth nearly tip positions and nearly tooth bottom positions from the derivative values
3. Detect two medians between nearly tooth tip points and nearly tooth bottom points from the laser measured data
4. Count the numbers of sampling points between each detected points
5. Calculate gear rotating speed $\omega_m$ (rad/s) by using this formula. It is average for each detected points

$$\omega_m [\text{rad/s}] = \frac{\theta_m}{t_s} = \frac{2\pi}{n_i z}.$$  

- $\omega_m$: Gear rotation speed while laser measuring [rad/s]
- $t_s$: Sampling period of laser measuring [s] = const.
- $\theta_m$: Derived angle of gear rotation shaft [rad]
- $n_i$: Number of sampling points ($i = 1, 2, 3, \ldots$)
- $z$: Number of targeted gear teeth

- Convert the gear rotating speed the discrete values data(left graph) to the continuous value data(right graph) by using cubic spline interpolation
5.3 Diagnosis experiment without using a rotary encoder

To confirm the validity of this method, we conducted an experiment using the procedure described above. Figure 7 illustrates the detection of the damage range and the distance from the tooth tip. In this experiment, the mean data of all teeth were used as the benchmark (Data C in Fig. 3). Table 1 shows the test gear specifications and data measured directly using a caliper directly for this experiment. The tooth surface of tooth number 9 of this gear has a scratch that was created intentionally with a center punch as shown in Fig. 8. Therefore, a voltage spike should be detected in the subtracted data (i.e., the subtraction of Data C from Data B shown in Fig. 3). We measured the data for the laser reflection from the gear using the device described previously (Tanaka, et al., 2013a). The DC motor rotation fluctuated intentionally in accordance with the triangular wave as the laser measurement was performed as shown in Fig. 9, and the base rotational velocity \( V \) was set at 30, 50, and 100 [r/min]. The amplitude value \( a \), as shown in Fig. 9, was also set at three different values of 8, 16, and 25 [r/min]. Therefore, the maximum speed was 125 [r/min], and the minimum speed was 5 [r/min]. The cycle of the gear rotational fluctuation \( T \) in Fig. 9 was set at seven different patterns of 0.10, 0.25, 0.50, 1.00, 3.00, 4.00, and 5.00 [s].

An example of the subtracted data (subtraction of Data C from Data B shown in Fig. 3) is shown in Fig. 7 (upper right). (Experimental condition: \( T = 0.50 \) [s], \( a = 16 \).) The arrow-like spike in Fig. 7 arises from the tooth surface damage. Using this data, we calculated the damage range and distance from the tooth tip in accordance with the definition, as shown in Fig. 7 (lower right, enlarged view of the 9th tooth). In the case of this test gear, as shown in Fig. 7, the error range of the subtracted data and all the other data was within \( \pm0.03 \) [V], and it is impossible to detect the data corresponding to the damage in this range. Therefore, we defined the upper 0.03 [V] of the spike as arising from the damage on the tooth surface. This threshold ensures that only the spikes from the damage will be used in this method.

Using the angle variation data \( \theta_{11} \) [deg] and \( \theta_{12} \) [deg] in this figure, we can convert to the lengths of the damaged range \( x_1 \) [mm] and distance \( x_2 \) [mm] from the tooth tip using Eqs. (1) and (2). Figure 10 shows the detailed definition of each length on the gear tooth surface. The length \( l \) [mm] from the base circle to the tooth tip along the gear tooth surface can be calculated from \( \theta \), which in turn can be derived from the gear specifications. \( l_3 \) [mm], \( l_4 \) [mm], and \( x_1 \) [mm] shown in Fig. 10 can be measured using a caliper directly. \( l_4 \) [mm] can be calculated from \( l_1 \) [mm] and \( l_2 \) [mm]. \( l_2 \) can be calculated from \( l_3 \), \( l_4 \), and \( l \). \( l_2 \) can be also be simultaneously calculated from the laser reflection data. In this experiment, we compared each difference of the lengths \( x_1 \) [mm] and \( x_2 \) [mm] in Fig. 10, as derived from the data measured using a caliper and the laser reflection data, respectively.

Given these results, we can detect a prominent spike on tooth number 9 (graph in Fig. 7), with the spike indicating the damage. The damaged range and location errors diagnosed using data obtained without using a rotary encoder (new method) and those obtained using a rotary encoder of each base rotational speed are calculated and presented with contour maps, as shown in Figs. 11 and 12. The error [%] in Figs. 11 and 12 indicates the percentage of calculation error of the value obtained as the difference between the values obtained from laser reflection data and those measured directly using a caliper.

Examination of these results shows that the error, both \( x_1 \) and \( x_2 \), are negative. The results obtained without using a rotary encoder were worse than the results obtained using a rotary encoder by -5 to -10 [%]. In the case of the results obtained using a rotary encoder, the error value is almost constant, \( x_1 \): -20 [%] and \( x_2 \): -5 [%]. In contrast, the error value of the data obtained without using a rotary encoder was worse with the error exhibiting a dependence on the lower velocity \( V \) [r/min]. The relationship between the data measured using a caliper and those calculated from the laser reflection data is shown in Fig. 13. The values calculated from the laser reflection data are indicated by the subscript “laser”. As the velocity \( V \) decreases, the detecting point of the damaged edge (start point \( p \) and end point \( p_2 \)) in Fig. 13) delays. In particular, in the case of \( p \), the laser beam enters the damaged area, the pit is dented and the initial incidence angle is low. Therefore, it is difficult to reflect the laser beam at this point. The laser beam has a thickness, and it is difficult to detect \( p_1 \) after the full thickness of the laser beam enters the damaged area. Therefore, we assumed that the error in \( l_{\text{laser}} \) was bigger than that for \( l_{\text{caliper}} \). In this case, the errors of both \( x_{1\text{laser}} \) and \( x_{2\text{laser}} \) became negative.

Finally, we defined the limit condition to utilize our newly-developed method. As mentioned above, this method uses four points per tooth. From the sampling theorem, we defined the equation of the limit condition as follows:
where \( n \) [r/min] is the rotational velocity of the gear. When \( n = V - a \), \( V = 30 \) [r/min], and \( a = 8 - 25 \) [r/min], the limit area can be shown in contour maps, as shown in Fig. 14. Examination of the thickness of these contour maps shows that the result obtained for the upper right area was worse than that for the other areas. Therefore, the effectiveness of our defined limit condition can be confirmed. However, it is better to use this method in the conditions where the left-hand side value in Eq. (4) is larger than the right-hand side value by as much as possible. As part of a future work, we will also define the high rotational speed limit taking into account the processing speed of AD-board in PC.

\[
2 \cdot z \cdot \frac{n}{60} > \frac{1}{T_f} \tag{4}
\]

![Image of a diagram showing how to detect the damaged range and the distance from the tooth tip](image)

**Fig. 7** How to detect the damaged range and the distance from the tooth tip

| Table 1 Gear specifications and data measured using a caliper |
|-------------------------------------------------------------|
| Gear type | Spur Gear |
| Module \( m \) [mm] | 3 |
| Pressure angle \( \alpha \) [deg] | 20 |
| Number of teeth \( z \) | 20 |
| Pitch circle diameter [mm] | 60 |
| Tip diameter [mm] | 66 |
| Root diameter [mm] | 52.5 |
| Face width [mm] | 30 |
| Grade (JIS B 1702-1, JIS B 1702-2 (1998)) | N8 |
| Material | SUS303 |
| Damaged tooth number | 9 |
| Damaged range [mm] | 1.35 |
| Distance from tooth tip of the damage [mm] | 1.95 |
Fig. 8 Damage on the tooth surface (Tooth No. 9)

Fig. 9 Triangular wave for DC motor rotational fluctuation

Fig. 10 Detailed definition of each length on the gear tooth surface
Fig. 11 Error of the damaged range $x_1$ evaluated from the difference between the data measured using a caliper and calculated from the laser reflection data.

(a) $V=100$ [r/min] (Left: w/o encoder, Right: with an encoder, unit: %)

(b) $V=50$ [r/min] (Left: w/o encoder, Right: with an encoder, unit: %)

(c) $V=30$ [r/min] (Left: w/o encoder, Right: with an encoder, unit: %)
Fig. 12 Error of the distance $x_2$ evaluated from the difference between the data measured using a caliper and calculated from the laser reflection data.

(a) $V=100$ [r/min] (Left: w/o encoder, Right: with an encoder, unit: %)

(b) $V=50$ [r/min] (Left: w/o encoder, Right: with an encoder, unit: %)

(c) $V=30$ [r/min] (Left: w/o encoder, Right: with an encoder, unit: %)
Fig. 13 Relation of the data between measured using a caliper and calculated from the laser reflection data

Fig. 14 Boundary of the range for which our proposed method can be used is shown in contour maps in Figs. 11(c)left and 12(c)left (Left: Error of $x_1$, Right: Error of $x_2$, $V=30$ [r/min])

6. Conclusions

We developed a new method that enables us to diagnose damage on a gear tooth surface without a rotary encoder. Based on the experimental results on teeth surface diagnosis using the new method, we reach the following conclusions:

1) The results without using a rotary encoder were worse than the results using a rotary encoder by -5 to -10 [%].
2) The base rotational velocity affects the accuracy.
3) The limit conditions for the use of this new method can be defined.

Installation cost will drastically decrease using this method; moreover, this diagnosis method is easy to set up. However, the accuracy of the method is slightly lower than that of the previously developed methods. We are now planning to use this method in practical in gear machine manufacturing factories. Therefore, we must develop a compact unit to enable easy and low-cost worldwide use of this method.
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