

Prediction of Mesh Misalignment of External Gear for Transmission

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ABSTRACT

To increase the accuracy of meshing analysis of the external gear of the transmission, attention was focused on mesh misalignment of the gear. A gear in an actual vehicle is supported by a number of parts. An appropriate fitting stiffness was assigned to the point of contact between the gear and each support part, and a misalignment theoretical prediction technology having feasible accuracy and calculation times was constructed using linear analysis. By applying misalignment created using the method described in this paper to gear mesh analysis, it was confirmed that there was good correlation with the actual status of gear tooth flank contact and damage prediction. Also, analysis on the misalignment effect factors and their role in misalignment was possible as well, which made efficient reduction of misalignment possible.

1. Introduction

In recent years, reduced-weight automobile transmissions are being demanded in order to reduce CO₂ emissions and increase fuel economy. On the other hand, due to there being increases in engine torque and the increasing need for development of high-weight automobiles represented by SUV (sports utility vehicles), the load on the power transmission parts, such as the gears, is increasing.

For this reason, the shaft, bearings, housing, and other parts that support the gears undergo elastic deformation⁽¹⁾ due to load. In addition, because there are clearances between the parts that support the gears, the gear pairs are operated in a condition different from that of normal meshing conditions. It is necessary that the gears have adequate strength under such a condition. Consequently, in designing gear strength, it is necessary to take into account the meshing conditions. Methods of designing gear strength that take into account the meshing condition have already been proposed⁽²⁾.

However, in the calculation of shaft stiffness alone, which had been performed during the conventional design stage, other factors were not taken into consideration, and calculation accuracy that matched an actual vehicle could not be obtained about the meshing condition of a gear pair. Also, although there is a method of observing the

contact condition of the tooth flank when the vehicle is actually being driven, this method cannot confirm it before the vehicle is completed, and it is challenging from which to make a quantitative judgment. Accordingly, in this paper, factors other than the shaft (the bearings, housing, and clearance between the gear support parts) were also considered at the design stage, and the meshing condition of a gear pair could be predicted in a more practical calculation time and to a more practical degree of accuracy. A report is set out below.

2. Conventional Prediction Technology and Related Issues

While a gear pair is meshing, the relative displacement of the shaft that occur in the direction of line of action at the effective face width ends are defined as Al_1 and Al_2 . The difference between them is called the misalignment and is defined as AL (Fig. 1).

$$AL = Al_1 - Al_2 \quad (1)$$

Previously, prediction of the misalignment at the design stage was done using a shaft deflection analysis program, which only took into account shaft stiffness. However, the gears are supported by multiple parts, and there are clearances between the respective parts (Fig. 2). Consequently, accurately predicting the misalignment from

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only the shaft stiffness is challenging⁽³⁾, and the influence of other factors could not be determined, so issue was that much testing was necessary to analyze the root cause of misalignment and to perform enhancements.

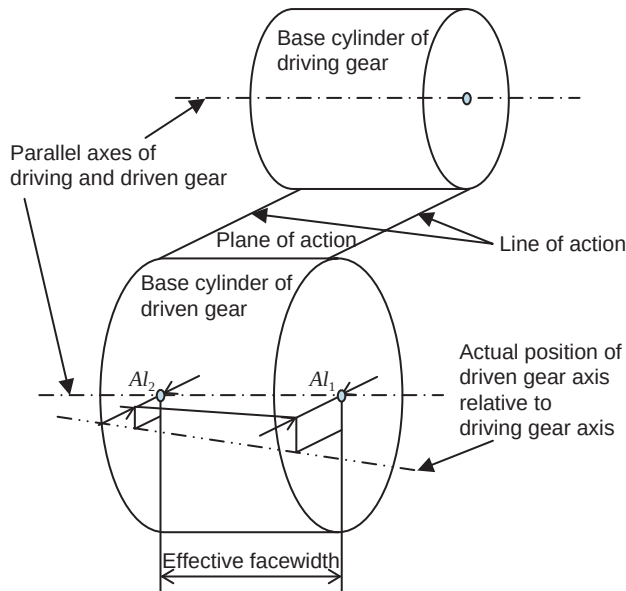


Fig. 1 Definition of mesh misalignment

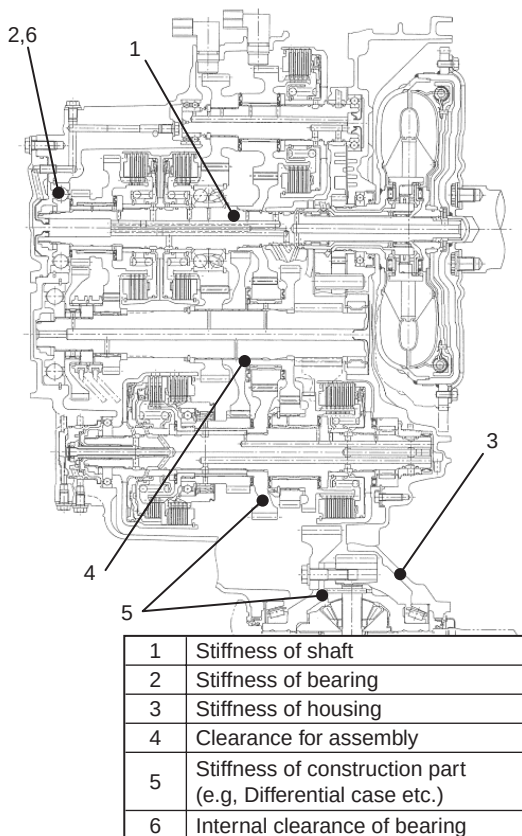


Fig. 2 Factor of mesh misalignment

3. Establishing Misalignment Prediction Technology

In the establishment of misalignment prediction technology, the displacement of the gears, shaft, and bearings in an actual vehicle were measured, and the correlation of the analysis results with an actual vehicle was validated.

3.1. Measurement of Each Displacement in an Actual Vehicle

The displacement of the gears, shaft, and bearings was measured using a torsion tester on a transmission bench. In order to reduce the influence of sticking, the absorption side was not fixed and measurement was performed at extremely low rotational speed by means of a powder brake. Figure 3 shows the configuration of the measuring equipment. In order to measure the displacement of the object parts, a laser displacement sensor, a linear gauge, and an eddy current gap sensor were used. Also, regarding the housing, shape optimization technology⁽⁴⁾ was used to fabricate and use a housing that has the stiffness of an actual vehicle, from which parts that interfered with measurement had been excluded, and which did not affect the support stiffness of the gear [Fig. 4(a)]. An example of the displacement measurement position of a gear is shown in Fig. 4(b).

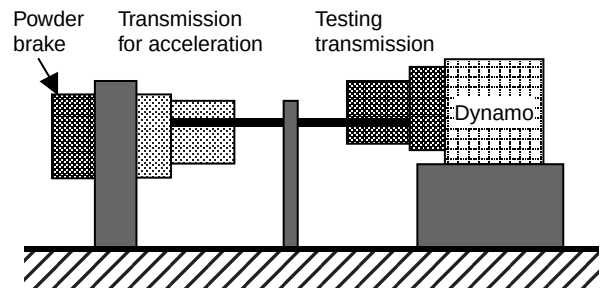


Fig. 3 Structure of testing equipment

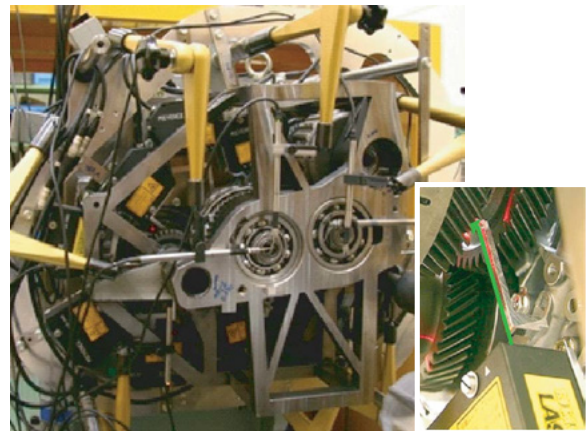


Fig. 4(a) Appearance of testing equipment

3.2. Outline of Misalignment Analysis Model

Figure 5 shows an outline of the misalignment analysis model. The shape and material characteristics (Young's modulus and Poisson's ratio) of each part are defined. The fitting stiffness between parts is defined for each pair of parts. A model for one transmission is made,

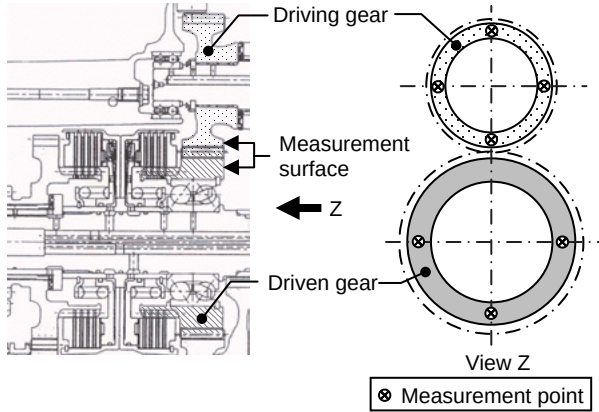


Fig. 4(b) Measurement point of gear displacement

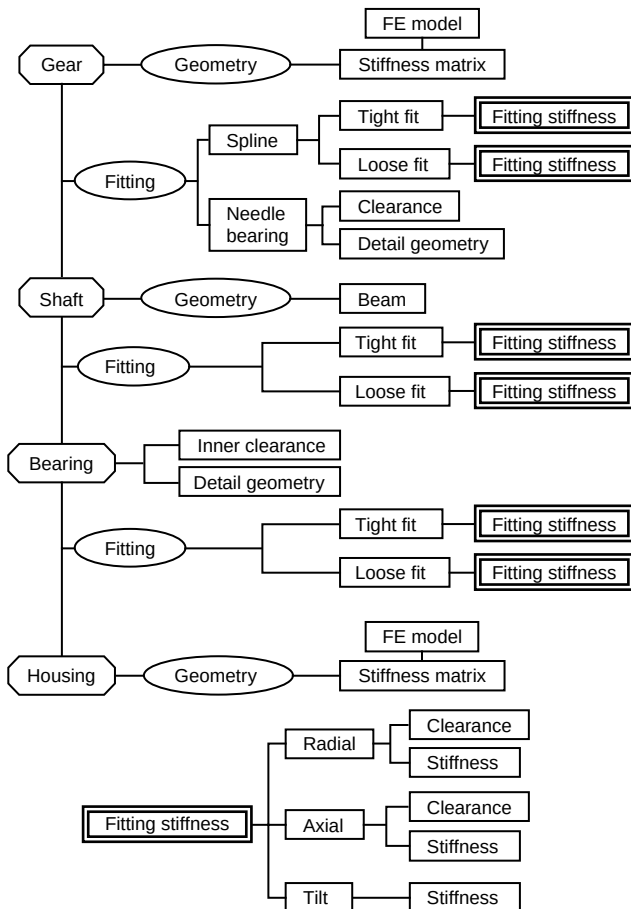


Fig. 5 Outline of mesh misalignment analysis model

the stiffness of each part and defined fitting stiffness between parts are coupled by linear analysis and the misalignment is calculated.

3.3. Fitting Stiffness Definition

In the misalignment analysis model, the fitting stiffness that is defined between parts should be defined for each pair of parts in the radial direction, axial direction, and tilt (Fig. 5). Regarding this fitting stiffness, if a uniform value is used irrespective of the location, correlation between the measured and calculated results could not be

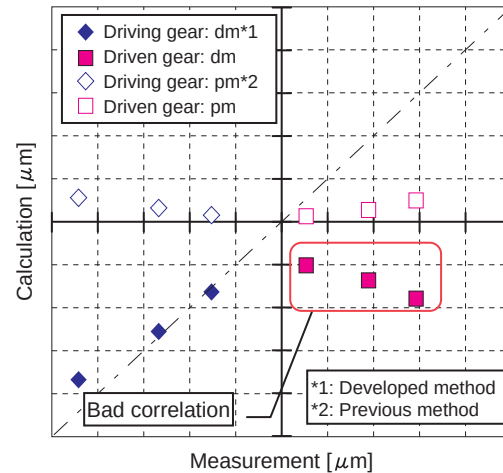


Fig. 6 Correlation of mesh misalignment

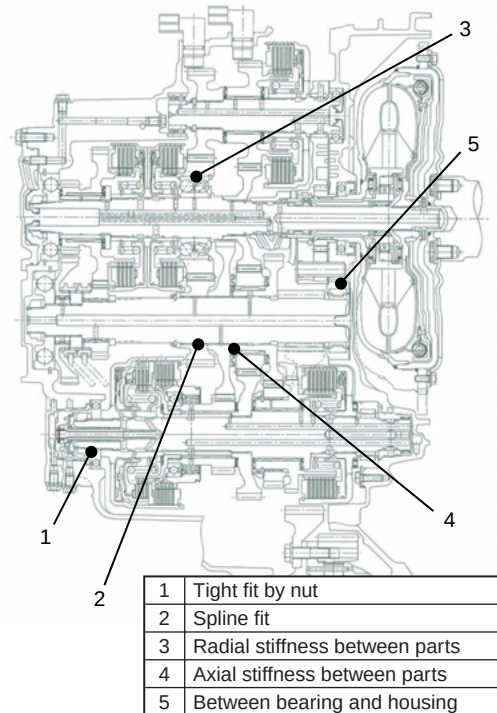


Fig. 7 Stiffness item definition

acquired, like the case of the conventional prediction method (Fig. 6). Accordingly, the measured results and the contact analysis were compared concerning the displacement of gears and gear support parts, using multiple transmission structures, and in order to acquire correlation with an actual vehicle, an appropriate fitting stiffness was defined for each component element shown in Fig. 7.

3.3.1. Radial direction fitting stiffness definition

As an example of fitting stiffness in the radial direction, the process concerning the definition of the fitting stiffness between the bearing and the housing is shown below. In linear analysis, the bearing load is added to the center node of the bearing hole in the housing. The center node and the bearing hole are connected to each other by a rigid bar. Consequently, the bearing hole in the housing is subjected to compression in the bearing load direction, and a tension force in the opposite direction. In contact analysis, the bearing load is applied to the rigid body, hence a compression force in the load direction acts in the bearing hole in the housing, but no tension occurs in the opposite

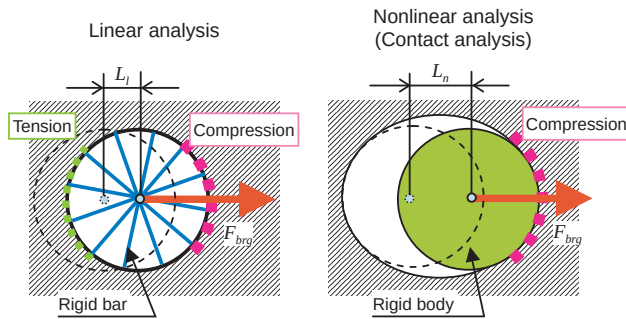


Fig. 8 Comparison of linear analysis and nonlinear analysis

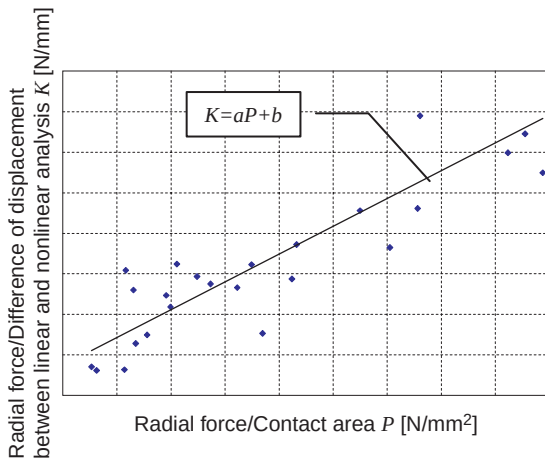


Fig. 9 Definition of stiffness between bearing and housing

direction (Fig. 8). Regarding the fitting stiffness in the radial direction between the bearing and the housing, the bearing load F_{brg} divided by the difference in the shift of the bearing center node ($L_n - L_l$) is defined as the fitting stiffness K . Also, the ratio between F_{brg} and the housing hole contact area A of the bearing O.D. (bearing O.D. $\times \pi \times$ bearing contact width) is defined as P .

$$K = \frac{F_{brg}}{L_n - L_l} \quad (2)$$

$$P = \frac{F_{brg}}{A} \quad (3)$$

The correlation between K and P was obtained by using multiple transmission structures (Fig. 9). Because a roughly linear relationship is obtained, the fitting stiffness between the bearing and the housing was defined by a linear equation (4) obtained from the above relationship.

$$K = aP + b \quad (4)$$

3.4. Gear Cross-sectional Shape

Regarding the cross-sectional shape of the gear, in the software used, there is a method of creating a gear as a shaft model, and a method of taking in the stiffness matrix as an FEM model. Regarding the end face displacement of the gear, the analysis results were compared with the actual results for both methods, and a method that takes in an FEM model that has higher correlation with an actual vehicle was employed (Fig. 10).

3.5. Misalignment Analysis Prediction Accuracy

A correlative comparison with measurement was performed regarding the conventional misalignment prediction technology (shaft deflection analysis) and the misalignment prediction technology established by taking into account the above-mentioned boundary condition definition. In contrast to the conventional prediction

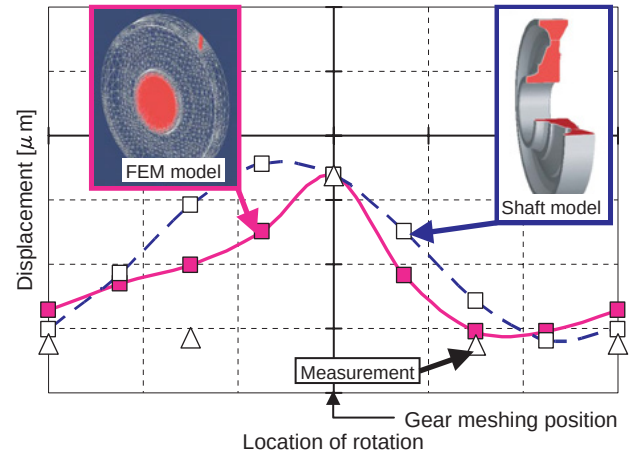


Fig. 10 Displacement of gear rim

technology, which only took into account the stiffness of the shaft, the new technology, established by taking into account the stiffness of the gear itself and the stiffness of the support parts, has enhanced correlation with measurement, and enables the design study accuracy of misalignment to be enhanced (Fig. 11).

3.6. Misalignment Analysis Time

As a method of calculating misalignment, non-linear analysis is also conceivable, but it involves the use of a large scale model, and issues concerning operability and calculation time (convergence) arise, so it can be impractical to use as an everyday design and development tool⁽⁵⁾. Figure 12 shows a comparison of the man-hours that is necessary for modeling and calculating the misalignment for one transmission. A comparison between

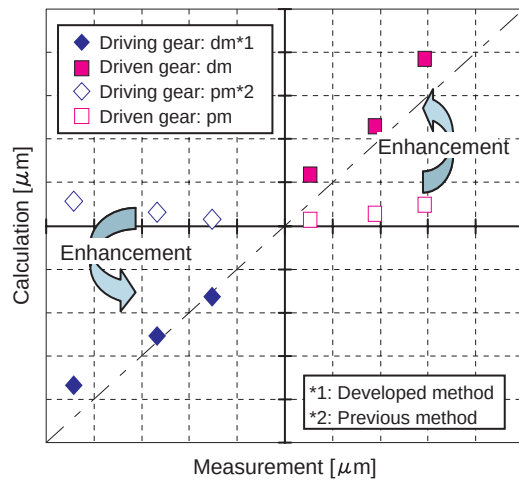


Fig. 11 Comparison of correlation for mesh misalignment

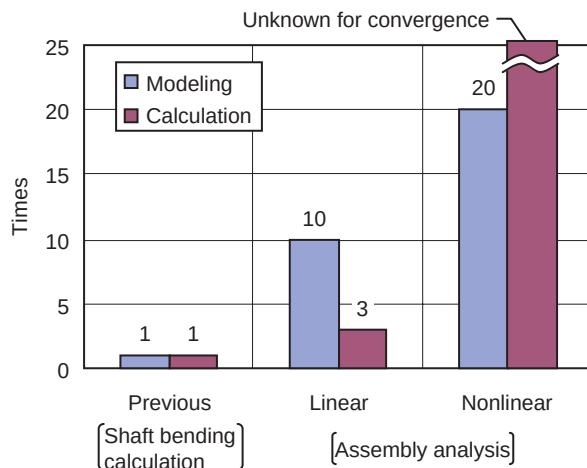


Fig. 12 Required time comparison for prediction of mesh misalignment

linear analysis and non-linear analysis (estimated values) was performed based on the modeling and calculation times of the conventional method. In this research, misalignment prediction technology was established using linear analysis.

In contrast to the conventional method, the newly developed method employs assembly analysis, so the modeling and calculation times increase. However, analysis in the assembly condition can be performed in several tens of minutes, and it was confirmed that the new method was a sufficiently practical method, even for everyday design and development, which necessitates calculations of a variety of conditions.

4. Actual Vehicle Test Conformity Validation

A gear analyzing program “GRANPLI”⁽²⁾, which permits the load distribution on the tooth flank when the gears are meshed to be calculated, was used taking into account misalignment and tooth profile, the gear meshing condition was analyzed, and the conformity of the newly developed technology to an actual vehicle test was validated.

4.1. Strength Test Conformity

In the development of transmission Type-A, pitting occurred on the tooth flank of the shift gears. Looking at the tooth flank, it can be seen that there is deviation of contact pattern in the tooth flank.

Regarding the driving gear and the driven gear, the contribution of the driving gear to misalignment is large (Fig. 13). An analysis of the factors responsible for misalignment was performed, and as a result, it was found that clearances and stiffness of the gear (cross-sectional shape) were the important factors (Fig. 14). Changing the clearances due to machining and assembly considerations poses a challenge, so the misalignment was reduced by

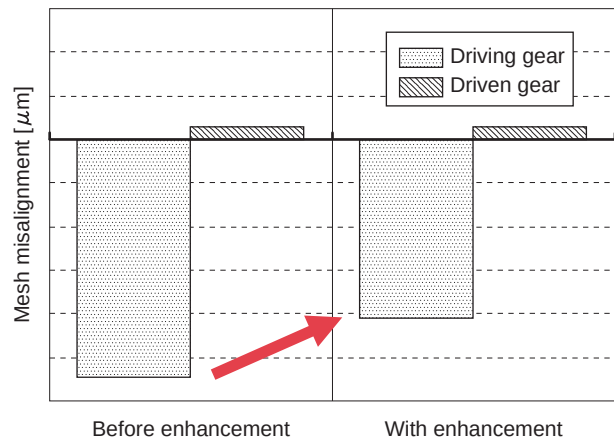


Fig. 13 Contribution rate of mesh misalignment (Driving gear and driven gear)

changing the stiffness of the gear (Fig. 15), and as a result, the tooth flank damage was reduced (Fig. 16).

4.2. Tooth Contact Test Conformity

The function of the transmission gears is to transmit

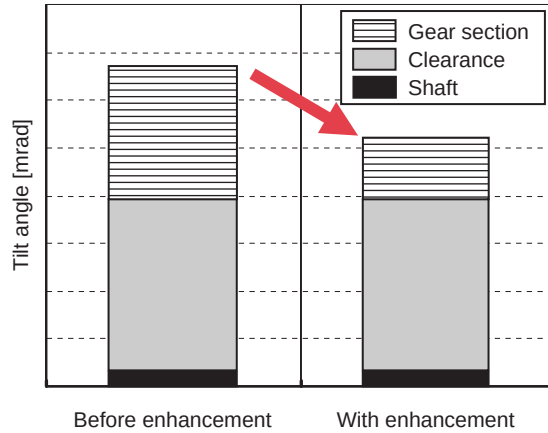


Fig. 14 Contribution rate of driving gear tilt

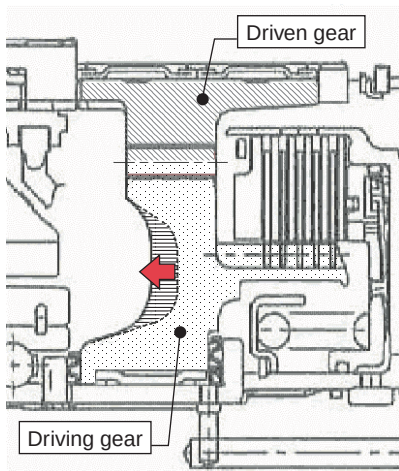


Fig. 15 Enhanced driving gear

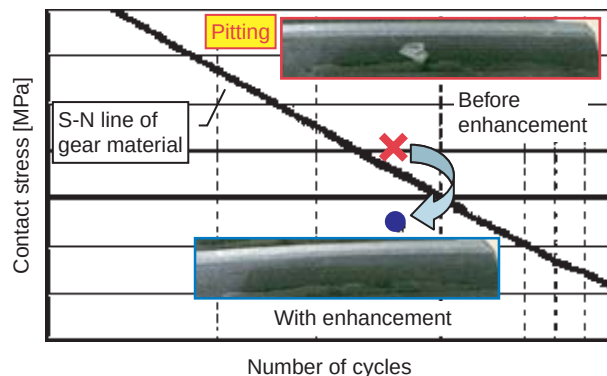


Fig. 16 Enhancement of gear flank damage

the output force from the engine to the drive wheels. From the viewpoint of marketability, noise vibration during meshing should be kept as low as possible. To this end, meshing should take place smoothly. The test used to check tooth flank meshing is a tooth contact test. The misalignment obtained using the conventional prediction technology (shaft deflection analysis), and the newly established prediction technology, were applied to "GRANPLI," and the calculated tooth flank meshing condition was compared with the actual vehicle tooth contact test results. By applying the misalignment obtained using the newly established technology to "GRANPLI," higher conformity with an actual vehicle was obtained compared to the use of conventional technology (Fig. 17).

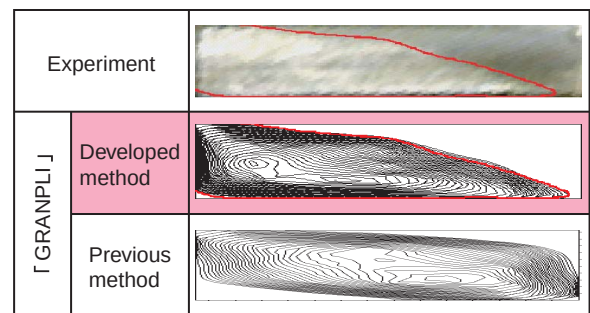


Fig. 17 Comparison of tooth contact patterns

5. Conclusion

Concerning the technology for predicting misalignment that affects gear meshing:

- (1) A method that provides results that have a higher degree of correlation with an actual vehicle, as compared to results obtained with the conventional prediction method, was established.
 - (2) By using linear analysis, results were obtained in a practical calculation time.
- Also, the following aspects were confirmed by means of an actual vehicle conformity validation.
- (3) By applying misalignment created by the newly established technology to the meshing analysis program "GRANPLI," the design prediction accuracy of the gear strength and tooth contact study was enhanced.
 - (4) By performing contribution analysis, it was found that the prediction accuracy was adequate for studying effective countermeasures against misalignment.

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