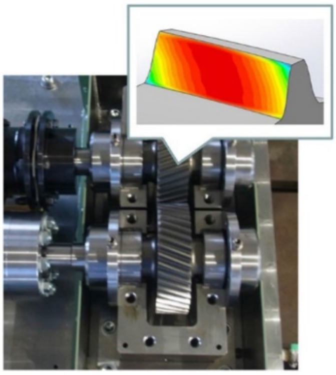
Improvement of Transmission Load and Noise Reduction by Optimally Design of Tooth Surfaces Using Principal Component Analysis



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With the background of social trends toward energy saving and advances in motor technology, drivetrains for vehicles such as automobiles have been electrified. Generally speaking, the output torque of a motor used as a prime mover with respect to the torque required for the product is small in many cases, so drive systems that combine a motor and a gear unit are often used to amplify the motor torque. Since these drive systems are required to be small and lightweight and to be very quiet, the gear unit must be improved in terms of the load capability and must have its vibration and noise reduced. It was difficult for conventional tooth surface modification design method to simultaneously improve the load capability and reduce vibration and noise. In this study, however, we made this possible by applying a shape representation method using principal component analysis to tooth surface modification design. This report describes an overview of the method and the results of the effectiveness verification.

1. Introduction

To improve the competitiveness of transmissions, overall optimizations such as noise reduction, reliability improvement and weight saving are needed. Currently, tooth surface modification is examined using simple modification parameters such as tooth profile modification and tooth trace modification[(1)]. It is difficult, however, for this method to generate complex shapes, so it has been difficult to achieve overall optimization design. Therefore, we applied a shape representation method using principal component analysis to tooth surface modification design in this study. As a result, it was made possible to efficiently generate tooth shapes that could not be represented by conventionally used design parameters and to examine the optimal tooth surface modification that can achieve both load capability improvement and mating excitation force reduction. This report describes an overview of the method and the results of the effectiveness verification with analysis.

2. Purpose of tooth surface modification

The meshing of gears is affected by “deformation due to load,” “gear error” and “stiffness variation due to meshing” as shown in **Figure 1**. These cause non-uniform tooth surface contact (tooth contact) and fluctuations in the gear rotational speed. Non-uniform tooth contact increases stress and reduces reliability, and fluctuations in rotational speed cause vibration and noise. Tooth surface modification is a method of intentionally generating a tooth surface shape that is different from the theoretical involute tooth surface for the purpose of making the tooth contact uniform and reducing fluctuations in the rotational speed in consideration of “deformation due to load,” “gear error” and “stiffness variation due to meshing.” Generally, as shown in **Figure 2**, tooth shape modification, which is tooth profile modification in the height direction, and tooth trace modification (crowning), which is tooth modification in the width direction, are applied. It was difficult, however, for these to optimally design load capability improvement and mating excitation force (vibration) reduction.

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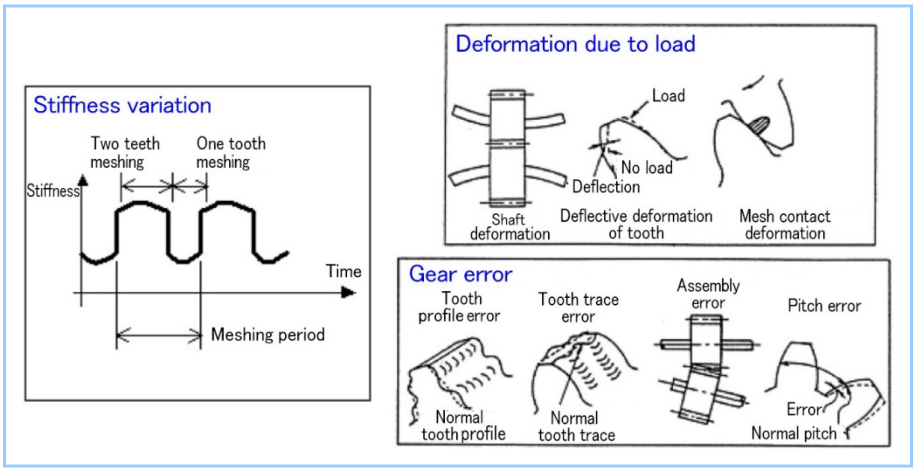

Figure 1　Factors affecting gear meshing

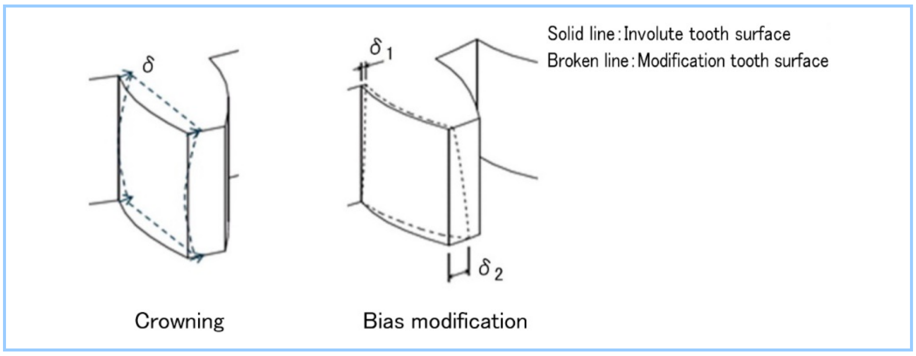

Figure 2　Generally used tooth surface modification method

3. Gear tooth surface design method using principal component analysis

In this study, we use the parameters obtained by principal component analysis as design parameters to express the tooth surface shape. The principal component analysis of a shape prepared in advance makes it possible to obtain new shape definition parameters different from the conventional modification parameters such as tooth profile modification and tooth trace modification. **Figure 3** depicts the flow for examining a tooth surface shape using principal component analysis. An overview of each process is described below.

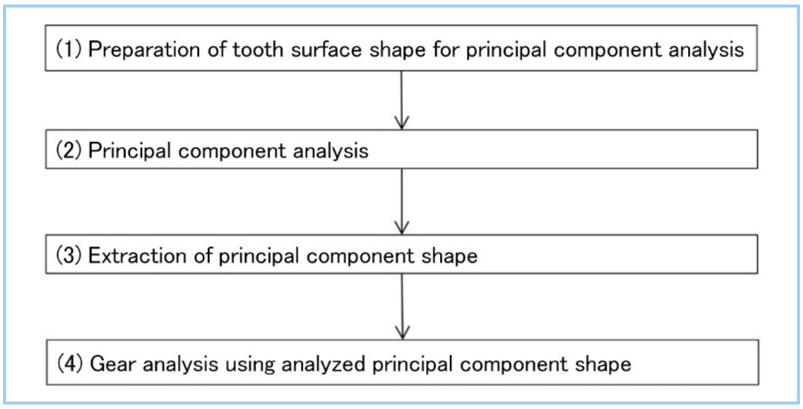

Figure 3　Flow for examining tooth surface shape using principal component analysis

(1)　Preparation of tooth surface shape for principal component analysis

The tooth surface shape for principal component analysis is generated using tooth surface modification parameters such as tooth profile modification, tooth trace modification and bias modification. At this time, the tooth surface shape is generated using a tooth surface design guideline used for designing a low-stress and low- mating-excitation-force tooth surface. This is intended to extract the characteristic amount of the tooth surface shape with low stress and low mating excitation force using principal component analysis.

(2) Principal component analysis

The prepared tooth surface shape data is converted into a matrix, and principal component analysis is performed on the matrix data. We used the proper orthogonal decomposition (POD) method[2] for principal component analysis.

(3) Extraction of principal component shape

The principal component shape (φ_j) is extracted from the results of principal component analysis. **Figure 4** gives examples of principal component shapes obtained by principal component analysis. The principal component shapes in Figure 4 are arranged by the amount of difference from the theoretical involute tooth surface.

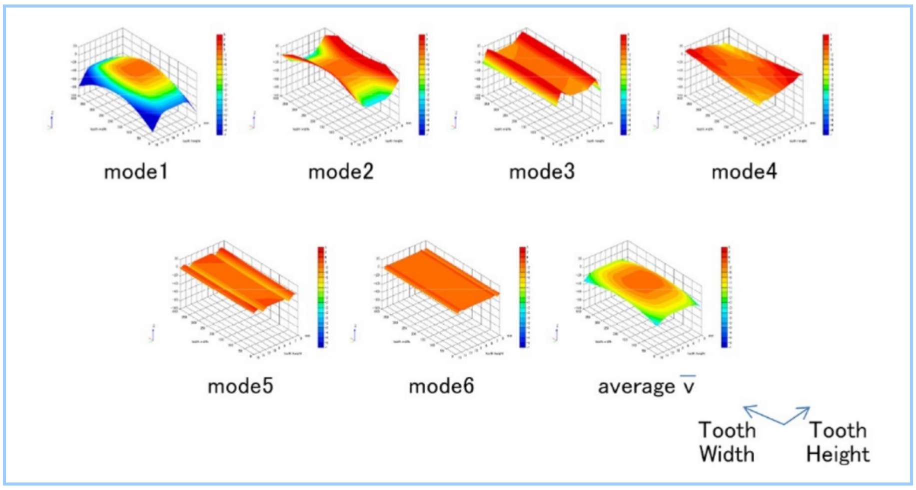

Figure 4 Examples of principal component shapes obtained by principal component analysis

(4) Gear analysis using analyzed principal component shape

Gear analysis is performed using the tooth surface shape ($\emptyset$) as a parameter, and the stress (surface pressure, tooth root stress) and the mating excitation force are evaluated to find a tooth surface shape that can both improve load capability and reduce mating excitation force. In this case, the tooth surface shape ($\emptyset$) is represented by the linear sum of the product of the principal component shape (φ_j) and the weighting coefficient (α_j) as shown in the following equation.

$$\emptyset = \overline{\boldsymbol{v}} + \sum_{j=1}^{n} \alpha_j \cdot \boldsymbol{\varphi}_j$$

where,

$\overline{\boldsymbol{v}}$: Average shape of tooth surface for which principal component analysis was performed

$\boldsymbol{\varphi}_j$: Principal component shape

α_j : Weighting coefficient (parameter)

4. Effectiveness verification with analysis

4.1 Comparison between the studied method and the conventional tooth surface modification design method

We verified the effectiveness of the studied technique by applying it to helical gears, which are used for industrial products. For the conventional method, we calculated the surface pressure and the mating excitation force by performing a parameter study on the tooth profile modification amount, tooth profile modification length, tooth trace modification amount and tooth trace modification length. For the studied method, we obtained the principal component shape using the method described in Section 3 and calculated the surface pressure and the mating excitation force by performing a parameter study on the weighting coefficient α_j. Tooth surface modification was performed only on the pinion side.

Figure 5 compares the calculated values of the surface pressure and the mating excitation force between the studied method and the conventional method. The surface pressure in this figure is represented by the maximum surface pressure of the tooth surface, and the mating excitation force in this figure is represented by the ratio of the primary component of the mating excitation force to the tooth surface transmitted load. This shows that the studied method attained a tooth surface modification shape with a lower surface pressure and a lower mating excitation force than the conventional method. From these results, the condition of the weighting coefficient αj for reducing the surface pressure and the mating excitation force simultaneously was obtained, and the optimal tooth surface shape was found.

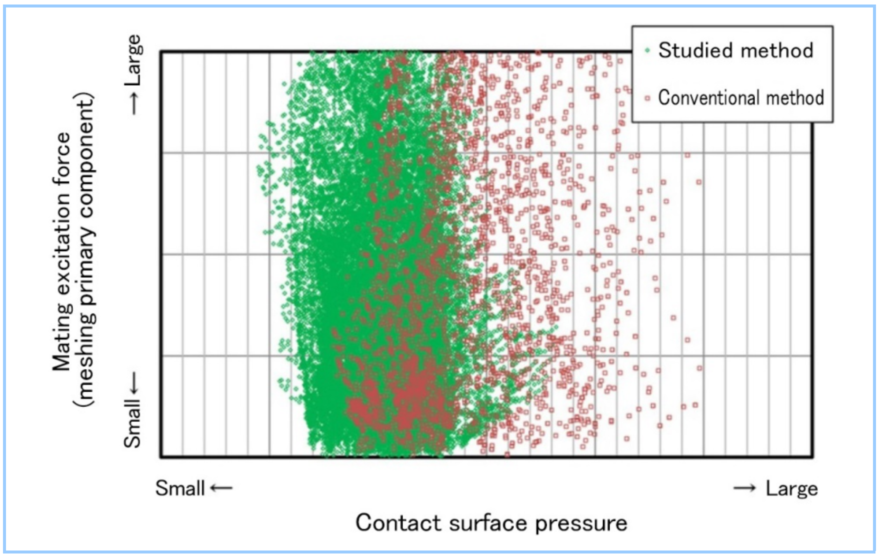

Figure 5　Analysis results of surface pressure and mating excitation force (comparison between studied method and conventional method)

4.2　Discussion

Figure 6 compares the surface pressure distribution between the tooth surface modification shape obtained by using principal component analysis and the tooth surface modification shape obtained by the conventional method (current specification), and **Figure 7** compares the mating excitation force between the two. It is indicated that the tooth surface modification shape obtained using principal component analysis had a lower surface pressure than the current specification due to the increased tooth contact area. In addition, the mating excitation force was reduced due to the optimization of the meshing length.

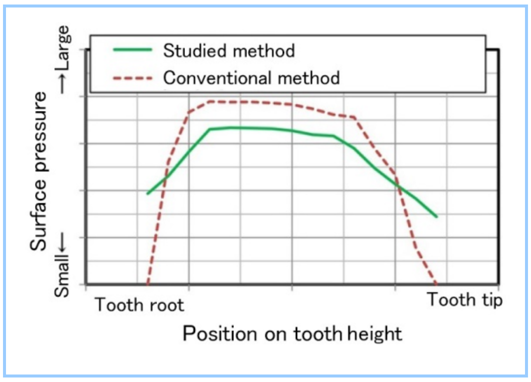

Figure 6　Surface pressure distribution with respect to position on tooth height (comparison between studied method and conventional method)

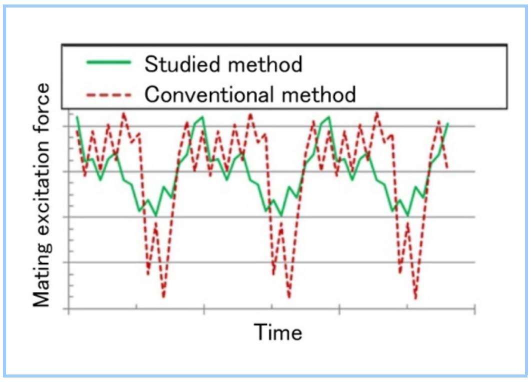

Figure 7　Time series waveform of mating excitation force (comparison between studied method and conventional method)

4.3　Estimation results of gear weight reduction amount

We estimated the gear weight reduction amount attained by applying the tooth surface modification shape obtained using principal component analysis. The design was made so that the surface pressure, PV value and mating excitation force would be equal to or less than the current specifications to prevent a decrease in strength and performance. **Figure 8** presents the estimation results of the gear weight reduction amount attained by making the module smaller than the current one and reducing the gear diameter. It was found that the gear weight could be reduced by about

21% compared to the current weight by using principal component analysis for the design of tooth surface modification.

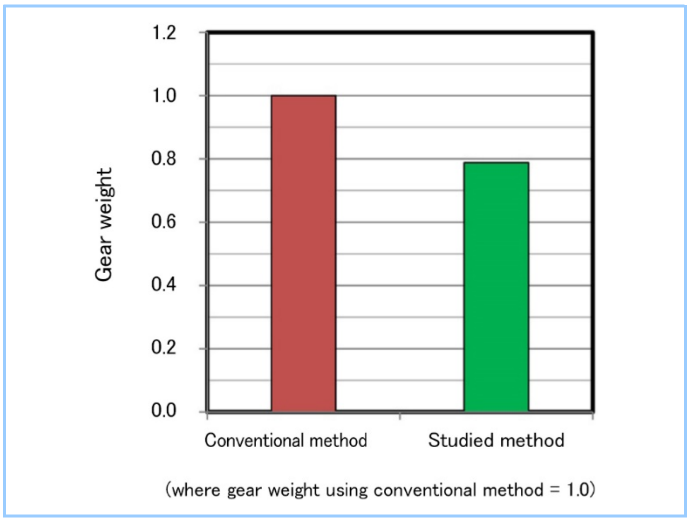

Figure 8　Estimation results of gear weight reduction effect

5. Conclusion

This paper described an overview of a gear tooth surface modification design method using principal component analysis and the results of effectiveness verification with analysis. The studied method can attain both higher load capability and lower mating excitation force than the conventional tooth surface modification design method, so it is considered to be effective in design for the downsizing of gear devices. We are currently verifying the effectiveness of this method by elemental test. After the verification is completed, we will promote its application to our products and further improve their performance and quality.

References

(1) Aizoh Kubo, Kiyohiko Umezawa, et al., On the Power Transmitting Characteristics of Helical Gears with Manufacturing and Alignment Errors, The Japan Society of Mechanical Engineers, Transactions of the JSME (in Japanese), Vol.43 No.371 (1977) p. 2771-2783

(2) L Sirovich, Turbulence and the dynamics of coherent structures, Quarterly of applied mathematics, Vol.45 No.3 (1987) 561-571