

Precise Calculation of Mesh Stiffness Fluctuation for Predicting Gear Noise

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Abstract: Nabtesco manufactures diverse configurations of reduction gears for varied applications in a wide range of industries worldwide. With changing markets demanding quieter operation, the perennial issue of noise generated by spur gears has become an even greater concern. Our traditional development strategy was designing gear shape modifications empirically and producing prototypes for testing. However, producing multiple gears and conducting noise evaluations is very cost and time intensive. We could not determine the exact effect various shape modifications would have on noise and why. While there are some long-established methods for analyzing gearbox noise, these methods are not appropriate for predicting gear shapes as size differences among gear shape modifications are much smaller than parameters established for gearbox noise evaluation.

Some research claims there is a strong relationship between mesh stiffness fluctuation and gear noise. Based on that, we focused on developing a method to calculate mesh stiffness precisely. Gears have mesh stiffness caused by elastic deformation of gear teeth. Abaqus can analyze gear contact effectively, however, using the normal configuration of contact analysis caused unexpected variations. In this paper, analyses were designed and conducted to calculate mesh stiffness with different models during gear rotation and then stiffness fluctuations among various gear shapes were compared. In addition, as contact algorithm affects the accuracy of mesh stiffness, a method for calculating the gear contact more precisely by using linear programming is incorporated.

Keywords: reduction gear, spur gear, noise, noise reduction, mesh stiffness, linear programming

1. Introduction

Nabtesco's reduction gears are widely used as joints in industrial robots. Recently, these robots have been used not only in factories but also in close proximity to humans. This requires gears to be quieter. It is known well that gear noise is a complex phenomenon. Empirically, we know that noise and vibration are mainly generated by spur gears in our reduction gears.

Spur gears are used in the first phase of reduction gear assemblies. Servomotor rotation is transmitted through the input gear to the spur gears, and speed is reduced according to the gear ratio between the input gear and the spur gears (Figure 1).

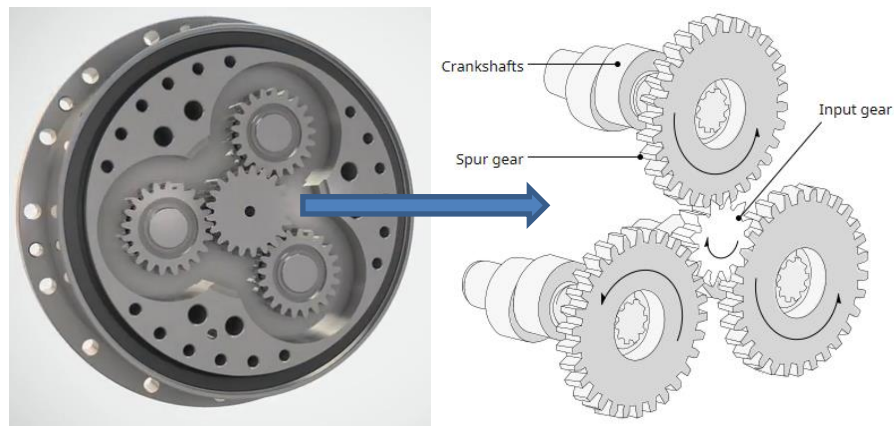


Figure 1. Input gear and spur gears in reduction gear assembly.

Among the factors affecting the generation of gear noise are gear tooth shape, elastic deformation of gears and gearboxes, machining tolerances, and assembly errors. But, from the design point of view, revising gear tooth shape is the most effective way of reducing gear noise.

However, it is very hard to determine the relationship between gear shape and noise by testing prototypes, because size differences among gear shapes are much smaller than the size of the gears and the effect of the other factors mentioned above cannot be eliminated.

2. Methods of calculating mesh stiffness fluctuation

According to previous research (Kasahara, 2014), there is a relationship between mesh stiffness fluctuation and gear noise. Figure 2 shows a general “mesh error” definition caused by tooth deformation and the number of teeth engaged. The “mesh error” curve is generated by calculating “mesh stiffness” as a function of the gear rotation angle.

The fluctuation of “mesh stiffness” leads to the fluctuation of shaft velocity and shaft vibration. Gearbox vibrations come from the shaft, through the bearings and cause noise.

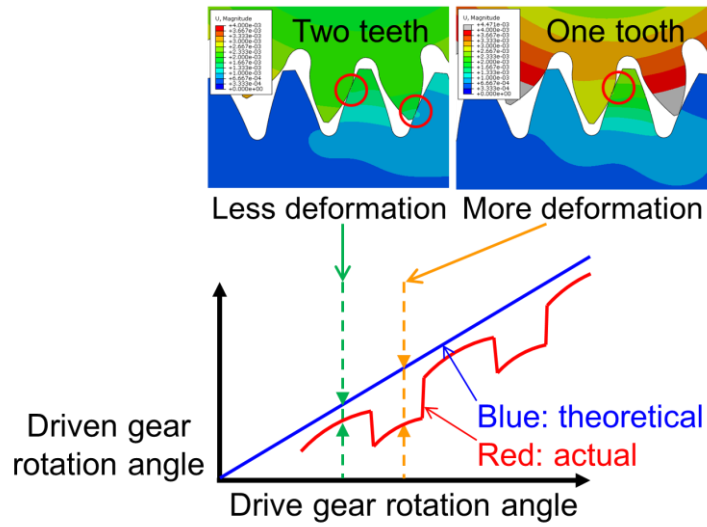


Figure 2. Gear deformation and gear rotation angle.

It follows that a gear shape with less mesh stiffness fluctuation would reduce gear noise. In this report, a method to analyze mesh stiffness fluctuation is reported.

Abaqus produces more convergence and more accurate results for contact analysis than other FEA programs. But, the preliminary results showed that the accuracy of the contact conditions of the gears was not sufficient due to the order difference between the problem scale and the model scale. (10^{-3} mm vs 10^2 mm). More detail follows in this report, but the calculation results of mesh stiffness using Abaqus were affected by contact algorithms and elements near contact areas. To counter this, a method of calculating mesh stiffness more precisely by using linear programming instead of Abaqus conventional contact algorithms was developed.

2.1 Analyzing mesh stiffness fluctuation using Abaqus

The analyses were conducted using 2D or 3D models of one input gear and one spur gear (Figure 3). The center hole of the spur gear was fixed, and torque was statically applied to the input gear. Abaqus/Standard with static, general procedure was used as the solver.

The mesh stiffness can be calculated by dividing load by deformation along the line of action of the input gear, expressed as:

$$k = P/\delta,$$

$$P = T/r_s,$$

$$\delta = \Delta\theta \cdot r_s,$$

where k is mesh stiffness, P and δ is total load and total amount of relative deformation along the line of action, T is torque applied to the input gear, r_s is the basic circle radius of the input gear, and $\Delta\theta$ is the rotation angle of the input gear after engagement.

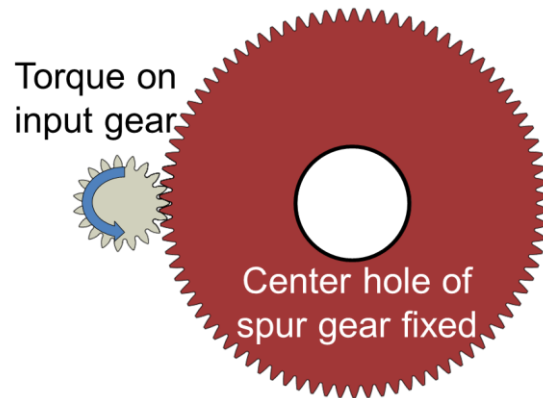


Figure 3. Analysis model.

Subsequently, both gears were rotated slightly to change the contact position (phase), and the mesh stiffness was re-calculated in each phase until tooth contact returned to the original position (Figure 4).

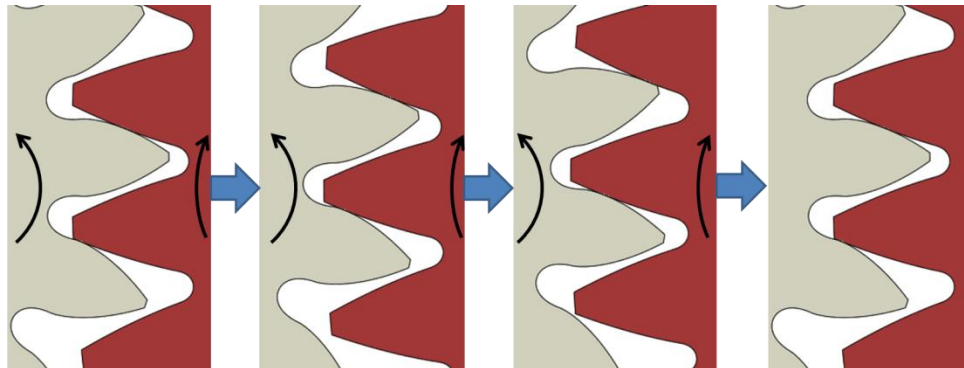


Figure 4. Gear rotation.

Originally, fine elements, which remained the same during rotation, were used along the entire gear tooth edge (Figure 5 (a)). The contact results were not accurate and calculation errors caused variations in mesh stiffness.

To compensate, elements near contact areas were re-meshed and the nodes in these areas were made finer, more aligned, which provided more precise results (Figure 5 (b)). Of course, elements in non-contact areas were coarse so the elements varied during gear phases.

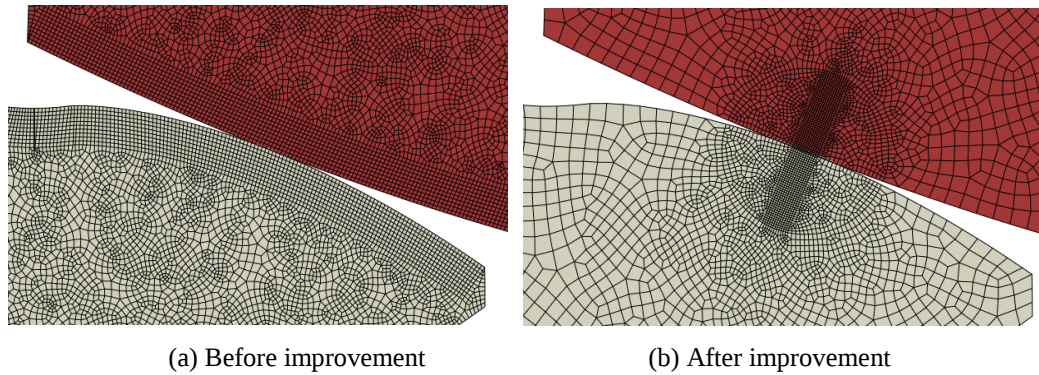


Figure 5. Elements near the contact area.

To confirm the effects of gear shape modifications along the gear tooth edge on mesh stiffness fluctuation, a 2D model with gear shape modifications was analyzed and compared to the results of a model without gear shape modifications (hereinafter “standard gear”).

In addition, to confirm the effects of gear shape changes along the gear tooth trace, a 3D model with gear shape changes was analyzed and compared to the results of a 3D model of a standard gear.

2.2 Analyzing mesh stiffness fluctuation using linear programming

The following steps show a method for calculating mesh stiffness more precisely by using linear programming instead of Abaqus conventional contact algorithm (Ishida, 1997).

1. Using this method, contact occurs in an area of predetermined width. The geometric center of this area is called the line of action as shown in Figure 6. Reference points on the area are defined as contact points, and corresponding points are created on the opposing gear’s surface.

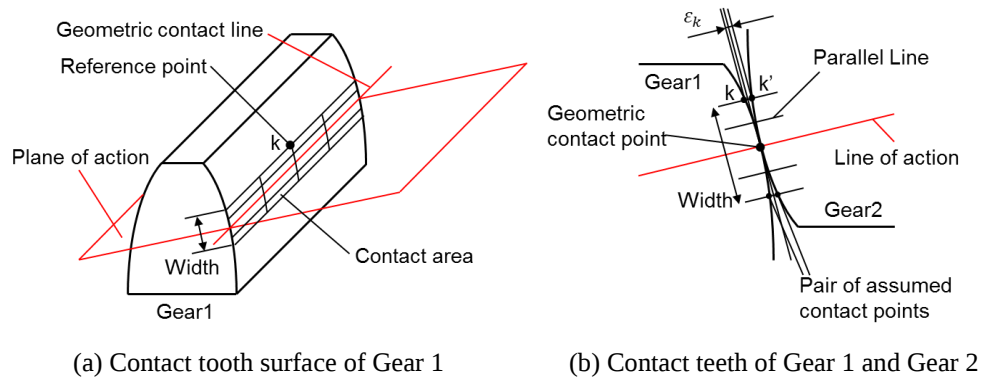


Figure 6. Face-contact model of a pair of spur gears.

2. The contact condition is calculated using linear programming (without FEA) for getting F_k and δ as follows:

Objective Function

$$Z = X_{n+1} + X_{n+2} + \dots + X_{n+n} + X_{n+n+1}$$

Constraint Conditions

$$\begin{aligned} -[S]\{F\} + \delta\{e\} + [I]\{Y\} + [I]\{Z'\} &= \{\varepsilon\} \\ \{e\}^T\{F\} + X_{n+n+1} &= P \end{aligned}$$

where

$$[S] = [S_{kj}] = [a_{kj(1)} + a_{kj(2)}], k = 1, 2, \dots, n; j = 1, 2, \dots, n$$

$$\{Z'\} = \{X_{n+1}, X_{n+2}, \dots, X_{n+n}\}^T$$

$$\{F\} = \{F_1, F_2, \dots, F_k, \dots, F_n\}^T$$

$$\{Y\} = \{Y_1, Y_2, \dots, Y_k, \dots, Y_n\}^T$$

$$\{\varepsilon\} = \{\varepsilon_1, \varepsilon_2, \dots, \varepsilon_k, \dots, \varepsilon_n\}^T$$

$$F_k \geq 0, Y_k \geq 0, \varepsilon_k \geq 0, \delta \geq 0, k = 1, 2, \dots, n$$

$$X_{n+m} \geq 0, m = 1, 2, \dots, n + 1$$

$a_{kj(1)}$ and $a_{kj(2)}$ are the amount of deformation on point k when unit force along a line of action is applied on point j of gear 1 and gear 2, and these are calculated by Abaqus. ε_k is the initial gap between two points (k and k' on Figure 7 (b)), and is obtained from the point's coordinates.

3. Mesh stiffness k was calculated as shown in section 2.1. using δ .

3. Results and Discussion

3.1 Results of mesh stiffness fluctuation using Abaqus

The mesh stiffness results of a standard gear (2D, blue line) and two type of gear shape modifications (2D, red line and green line) using the improved method are shown in Figure 7. The horizontal line indicates the gear phases. The numbers (1 or 2) in Figure 7 indicate the number of gear teeth engaging.

Also, the results of a standard gear using our previous method are shown as a purple line. It is obvious the line is not smooth and has calculation errors.

The blue line results (standard gear) have a clear gap between large mesh stiffness during two teeth engagement and small mesh stiffness during one tooth engagement.

The mesh stiffness of the red and green line (gear shape modifications) changes more smoothly than that of the blue line and duration of one tooth engagement have increased. This means these gear shapes may have some effects on reducing noise.

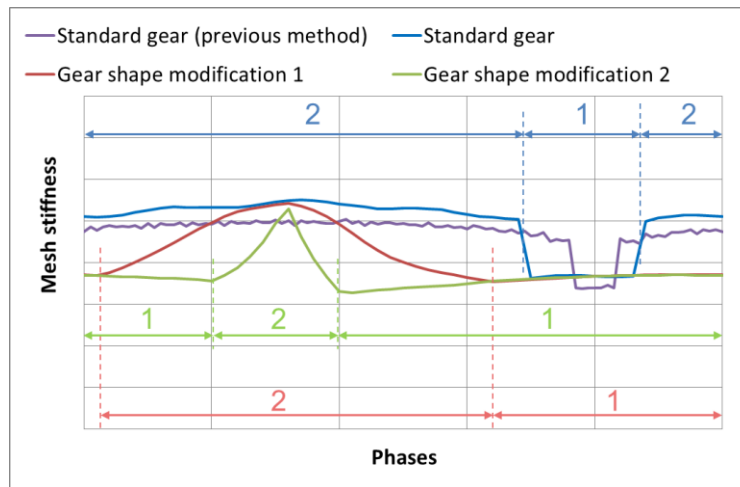


Figure 7. Mesh stiffness results of 2D models.

The mesh stiffness results of a standard gear (3D) and a gear with shape changes along the gear tooth trace are shown in Figure 8.

The gear with shape change has a smaller mesh stiffness value than the standard gear, and also less mesh stiffness fluctuation. This means this gear should produce less noise than standard gears.

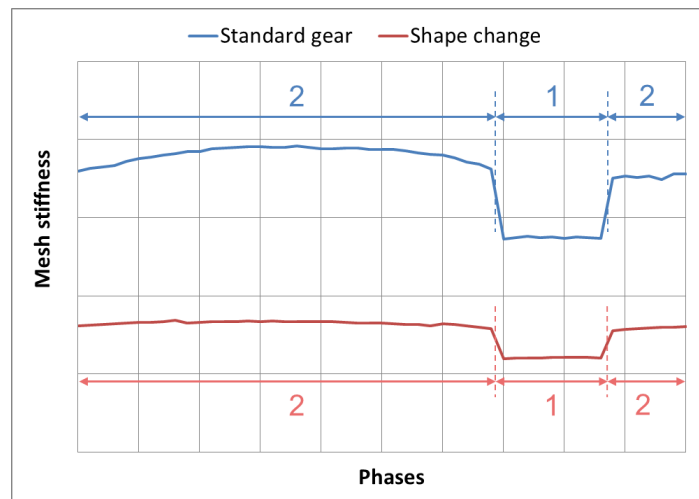


Figure 8. Mesh stiffness results of 3D models.

3.2 Analyzing mesh stiffness fluctuation using linear programming

The mesh stiffness results of a standard gear using linear programming are shown in Figure 9.

The results also have a clear gap of mesh stiffness but are not similar to the results using Abaqus (Figure 7 and 8) around the phase changing the number of engagement. The reason is that the contact force balance between the two contact points in the phases indicated by yellow triangles (in Figure 9) is not the same in the linear programming and Abaqus.

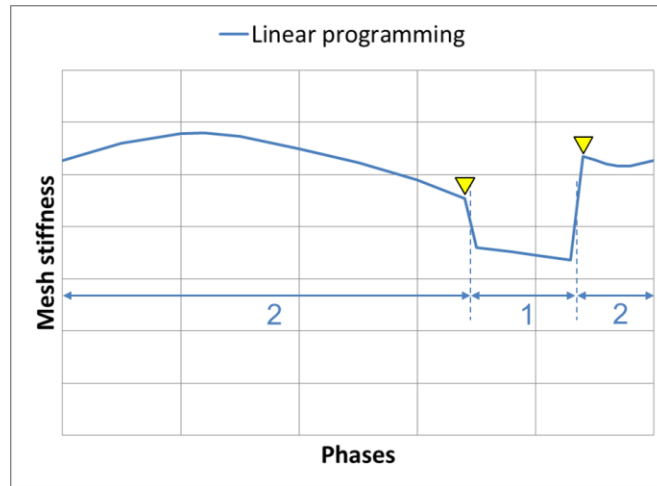


Figure 9. Mesh stiffness results using linear programming

4. Summary

- Methods to analyze mesh stiffness fluctuation as precisely as possible using Abaqus and linear programming were established.
- By using these methods, we can potentially design silent gear teeth and the development is ongoing.
- In this study, mesh stiffness fluctuation during static gear contact was evaluated, but dynamic fluctuation during gear rotation is also important and it should be taken into account. This will be considered at a later date.

5. References

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