Finite Element Analysis of Forces Generated by Gears with Defects

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Abstract

This work explores the use of finite element approach in analysing forces exerted in a gear pair containing a defect. Gears are the principal parts in rotating machinery and needs close attention and maintenance. Applications of gears where good maintenance is paramount are in machinery which is in use continuously, in applications where precise movement is needed and in the systems where safety is the prime concern, for example in airplanes and helicopters. Finite element models of a gear pair with and without a defect were developed. Various loading conditions were imposed. Resultant forces exerted on the rotation axes were analysed and compared between those of the damage-free and defective gear pairs. It was found that such forces in the defective gear pair could be as high as two times that of the healthy pair at the point where the defective tooth meshes.

1. Introduction

Gears are one of the main components used in power transmitting in various engineering applications. Prime examples are in electric utilities, automotive industry and in transportation. Most of their applications require the machinery to be functioning continuously and a sudden malfunction or breakdown can lead to disastrous results in terms of cost and safety for example. As a result, special attention is required to ensure that failure of such elements is understood and can be predicted. Gear failures are typically caused by fracture and/or wear. These two mechanisms, among others, induce defects within the gear. Some of the most common defects are root cracks, filled tooth and chipped tooth [1]. These are schematically shown in Figure 1.

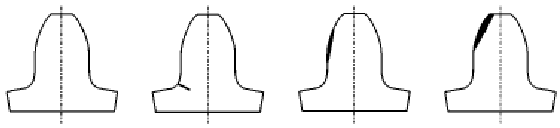

Figure 1. Typical gear defects; (a) healthy gear tooth, (b) tooth with a root crack, (c) filled tooth and (d) chipped tooth [1]

Gears containing defects such as a crack or a chipped tooth require rigorous analyses as they affect reliability and functionality standards. Overloading or fatigue conditions usually produce these defects. For the case of a crack, stress singularities are imposed. The study of a gearing failure demands both the approximation of failure itself and the complete simulation of gearing operation, which significantly complicates or renders the problem unresolved. Among the inherent difficulties in analysing such failures, the most important involve the complexity of the boundary shape, the coupling of solid body rotations and the evolution of rolling contact [2].

A single gear drive consists of two gears, where the input member is the 'driving gear' and the output member is the 'driven gear'. The operation of such a drive is characterised by the transmission ratio which is constant. The rotations take place through rolling of the mating teeth faces in a complicated operation that is known as conjugate action. To ensure rolling requirements, standard profiles have been established by gear manufacturers. They have irregular but regenerated shape known as involute geometry.

The presence of defects complicates this ideal operation and introduces more conditions and parameters. Numerical methods such as finite element [3-6] and boundary element [7] techniques as well as variational formulations [8] have been utilised to predict stresses in gear teeth for such cases.

This work investigates the influence of defects such as gear tooth chipping on the resultant forces exerted on the axis of rotation of both the driving and driven gears. The analysis is carried out using finite element technique. This is described in Section 2, followed by results, discussions and conclusions in Section 3 and 4, respectively.

2. Finite element models of a gear pair

Two finite element models of a pair of spur gears were developed. The first model consists of a driving and a driven gear without any damage, whereas the second model contains a defective driving gear. They both are made up of approximately 3720 nodes and 3388 elements. Two-dimensional linear plane strain elements are used for both models. Only a portion of each gear was modeled although a fully complete assembly can be analysed further. The FE model of the damage-free gear pair is shown in Figure 2.

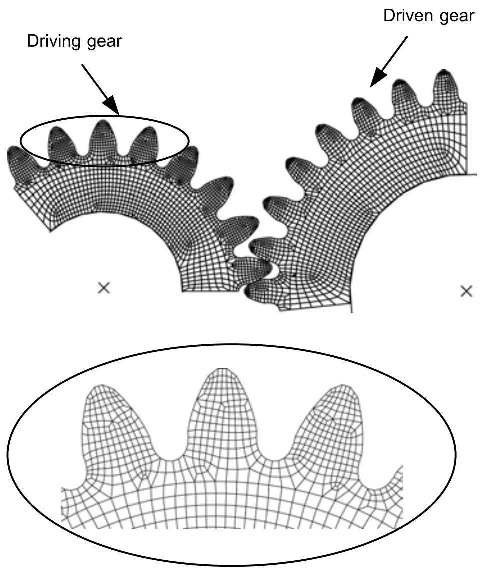

Figure 2. Finite element model of a damage-free gear pair

The prescribed boundary conditions for the damage-free gear pair are such that a uniform torque is applied to the centre of the driving gear while the driven gear is allowed to rotate, resisting the applied torque. Three levels of torque were applied. They are denoted by *T*, *2T* and *4T*, representing the base torque, the double and quadruple the magnitude of *T*, respectively. The gears are rotating at a constant angular velocity for half a revolution.

The gear defect considered here is the chipping of one of the driving gear tooth from the pitch point to the top. The outline of the model and the close-up view of the chipped tooth showing the FE mesh are shown in Figure 3.

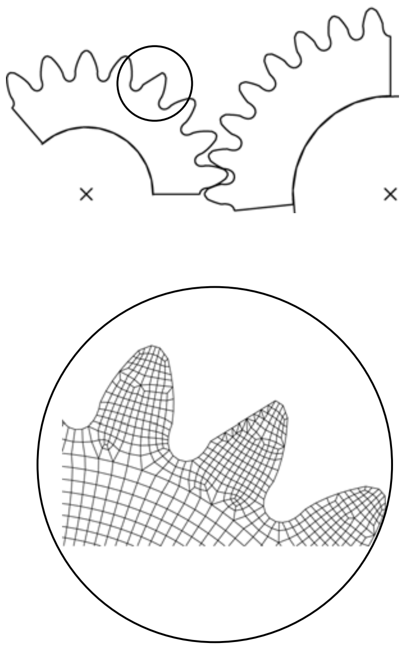

Figure 3. FE model of a gear pair containing a chipped tooth

The same boundary conditions as the damage-free gear pair was applied. The forces exerted on the axis of rotation for both driving and driven gears as well as the transmission ratio were analysed throughout the rotation for both models. The results are shown and discussed in the next section.

3. Results and discussions

The resultant forces at the centre of the rotation in the perpendicular in-plane directions for the three torque levels were normalised by the maximum valued obtained. They are denoted by *RF1* and *RF2*. Such results at the driven gear axis for the damage-free model are shown in Figures 4 and 5, respectively.

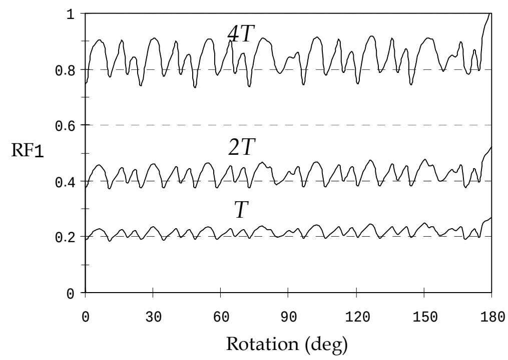

Figure 4. Normalised resultant forces (*RF1*) at the driven gear axis in the damage-free model

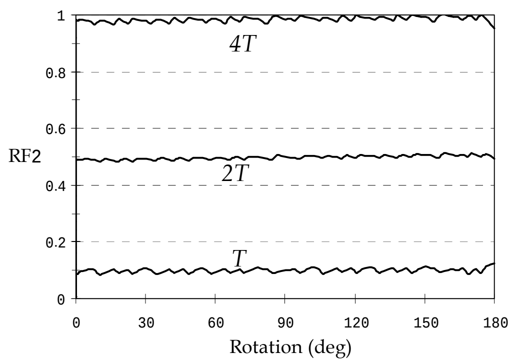

Figure 5. Normalised resultant forces (*RF2*) at the driven gear axis in the damage-free model

It can be seen from the figures that the resultant forces at the axis of the driven gear in both directions are proportional to the input torque. As expected, greater torques lead to higher resultant forces. These forces are not uniform throughout the rotatation although the variation is less so in the case of *RF2* compared to *RF1*. The non-uniformity is a result of the evolution of the rolling contact as the gears mesh. The same amount of forces acts on the axis of the driving gear but in the opposite direction and hence is not shown here for brevity.

The transmission ratio of the gear pair is shown in Figure 6 where non-uniformity is also observed. The mean value is around 1.38 with the greatest fluctuation of 5%.

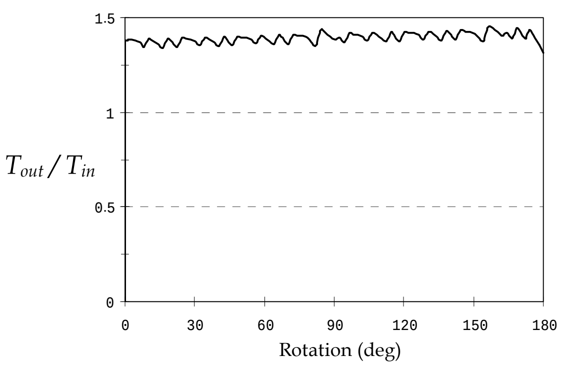

Figure 6. Transmission ratio of the damage-free gear pair throughout the rotation

Next, the corresponding resultant forces obtained from the defective gear pair are compared with those of the damage-free model. The values obtained from the defective model were normalised by those shown in Figures 4 and 5. Only the case of the applied torque *T* was shown although results for cases of *2T* and *4T* are indistinguishable. The comparison is shown in Figures 7 and 8.

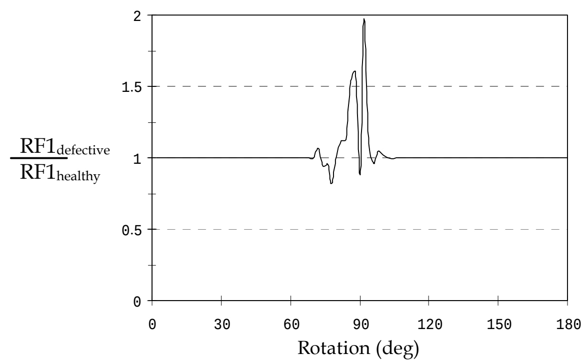

Figure 7. Comparison of the resultant forces (*RF1*) at the driven gear axis for the healthy and the defective models.

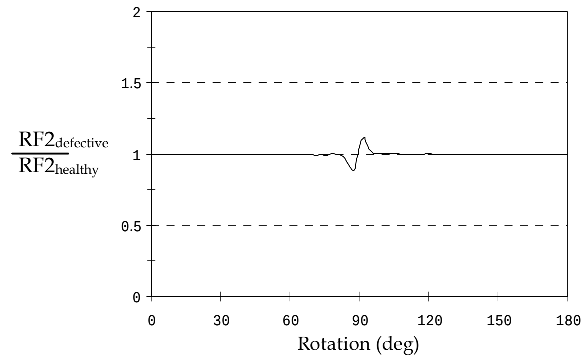

Figure 8. Comparison of the resultant forces (*RF2*) at the driven gear axis for the healthy and the defective models.

It can be seen from the figures that the existence of the chipped tooth in the driving gear causes the resultant forces in both directions to increase. A sharp increase by almost a factor of two is observed in the case of RF1 although in the case of RF2, it is less significant. The difference occurs when the chipped tooth is in mesh, which is around half way through the rotation.

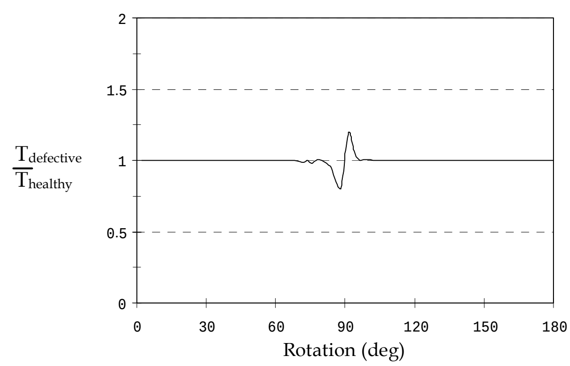

Figure 9. Comparison of the output torque of the defective and damage-free models

As expected, the characteristic of the output torque should be affected by the existence of the chipped tooth as well. This is confirmed in Figure 9 where the output torque of the defective pair is normalised by that of the healthy one. The figure shows the variation of the output torque to be as much as 1.25 times at the point of meshing of the chipped tooth.

4. Conclusions and recommendations

This work uses finite element method to analyse the resulting forces exerted on the axes of the gear pair throughout its rotation. Finite element models of a healthy and defective gear pair were developed. The defect considered is the tooth chipping in the driving gear. It was found that the resultant forces increase with increasing input torque as expected. The defective gear pair shows a rise in the forces and output torque compared to the healthy pair when the chipped tooth is in mesh. The difference is as high as two times in one of the forces.

The relationship between the severity of the defect and the resulting forces is not addressed in this work. However it is a subject of interest which should be investigated further.

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