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Effect of shaft misalignment and friction force on time varying mesh stiffness of spur gear pair

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ABSTRACT

Shaft misalignment and sliding friction between meshing teeth are considered as primary excitation to generate vibrations and extra dynamic loads on transmitting gear teeth. Time varying mesh stiffness (TVMS) is an important parameter to understand the dynamics of meshing gear pair. Potential energy method is one of the most acceptable methods to calculate TVMS. This paper proposes a computer simulation based approach to study the effect of shaft misalignment and friction on total effective mesh stiffness for spur gear pair. The results showed clearly that misalignment and friction affect TVMS of gear pair. The effect of misalignment and friction has also been studied for cracked gear pair and results are discussed.

1. Introduction

Gear system is one of the most common transmission systems used to transmit motion and power in various industries. In major industries condition monitoring and fault diagnosis of gear system is an important task. The vibration response of gear system plays an important role in fault diagnosis and condition monitoring.

Vibration response of gear pair is closely related to TVMS of the gear pair. Two methods are being widely used by researchers to calculate TVMS of gear pair, viz. finite element method (FEM) and analytical method (AM). Many researchers have proposed their analytical methods to calculate the TVMS of healthy and damaged gears. Yang and Sun [1] in 1985 proposed a value of Hertzian energy which is further extended by Yang and Lin [2] in 1987 to calculate TVMS of a gear pair by the potential energy method by including bending energy and axial compressive energy with Hertzian energy. This model was further refined by Tian [3] in 2004 by taking the shear energy into consideration. Tian [3] also discussed the effect of chipped tooth, cracked tooth and a broken tooth. Wu [4] presented the refined model of Tian [3] for faulty gear pair for calculating the total effective mesh stiffness as a function of crack length, crack intersection angle and rotation angle of gear for a pair of meshing spur gears consisting of a perfect gear and a pinion with cracked tooth. Wu et al. [5] studied the effect of crack growth in gear tooth on total mesh stiffness. They have also done dynamic modeling to simulate vibration response of meshing gear pair. Fillet foundation deflection proposed by Sainsot et al. [6] in 2003 is used by Chari et al. [7] in 2009 to develop a model to calculate the TVMS using potential energy method.

Chen and Shao [8,9] proposed an analytical mesh stiffness model of spur gear with tooth root crack propagating along both tooth width and crack depth. They have also included the effect of the gear tooth errors. Influences of the tooth profile

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modification, applied torque and gear tooth root crack on the mesh stiffness are also investigated. Pandya and Parey [10] have adopted principle of LEFM to carry out crack propagation path studies with different contact ratio and predicted the change in TVMS for different crack propagation path. Pandya and Parey [11] studied the effect of variable crack intersection angle on different gear parameters on TVMS. Pandya and Parey [12] performed the crack propagation path studies of spur gear using linear elastic fracture mechanics principle for two gear parameters. Pandya and Parey [13] presented an experimental methodology using photo-elasticity technique for computing stress intensity factor (SIF) for cracked spur gear tooth for different crack length. Zhou et al. [14] considered deformation of gear body for TVMS calculation of tooth root crack. Omar et al. [15] studied the influence of TVMS on vibration based fault detection indicators. Many other researchers [16–19] have done TVMS studies considering various gear parameters.

Investigation of gear mesh stiffness has been carried out extensively for healthy and cracked gears. But very less work is done on misalignment errors of spur gear pair. Ameen [20] in 2010 studied various effects of shaft misalignment on the stress distribution of spur gear using FEM technique. Recently Li [21] used FEM technique to study various parameters including the effects of misalignment errors on mesh stiffness of spur gear pair. Results show that due to misalignment errors mesh stiffness of spur gear pair decreases. In this paper TVMS has been calculated for spur gear pair mounted on misaligned shaft using potential energy method. Effect of friction force on TVMS for misaligned shaft has also been explored.

2. Potential energy model for time varying mesh stiffness calculation for spur gear pair

2.1. Mesh stiffness calculations for healthy spur gear pair

The gear mesh stiffness model used in this study is based on potential energy method proposed by Yang and Lin [2] in 1987 which is further refined by Tian [3] in 2004. The energy stored in meshing gear system was assumed to include four components out of which three components; Hertzian energy, bending energy and axial compressive energy is given in [2]; and fourth component; shear energy was proposed in [3]. Thus, for the single – tooth contact, the total effective TVMS can be expressed as [3],

$$k_t = \frac{1}{1/k_h + 1/k_{b1} + 1/k_{s1} + 1/k_{a1} + 1/k_{b2} + 1/k_{s2} + 1/k_{a2}} \tag{1}$$

where k_h, k_b, k_s and k_a represents the Hertzian, bending, shear and axial compressive mesh stiffness, respectively and subscripts 1 and 2 denote the driving and driven gears respectively. For the double-tooth pair contact, the total effective TVMS is the sum of the two pair's stiffness, which can be expressed as [3],

$$k_t = \sum_{i=1}^{2} \frac{1}{1/k_{h,i} + 1/k_{b1,i} + 1/k_{s1,i} + 1/k_{a1,i} + 1/k_{b2,i} + 1/k_{s2,i} + 1/k_{a2,i}} \tag{2}$$

where $i = 1$ represents the first pair of meshing teeth and $i = 2$ represents the second pair of meshing teeth.

2.2. Mesh stiffness of gear pair with a cracked pinion

If crack has been initiated at the root of a single tooth of a pinion then the above formula is not valid because bending stiffness and shear stiffness will change due to influence of the crack. This phenomenon will occur because when the crack is present, the effective area moment of inertia and the area of the cross section will change [3]. So, for single tooth mesh period the total effective mesh stiffness is given by,

$$k_{t\_crack} = \frac{1}{1/k_h + 1/k_{b\_crack} + 1/k_{s\_crack} + 1/k_{a1} + 1/k_{b2} + 1/k_{s2} + 1/k_{a2}} \tag{3}$$

where k_{b_crack} and k_{s_crack} are the bending mesh stiffness and shear mesh stiffness of cracked tooth respectively.

And for double tooth mesh period the total effective mesh stiffness can be written as,

$$k_{t\_crack} = \frac{1}{1/k_h + 1/k_{b\_crack} + 1/k_{s\_crack} + 1/k_{a1} + 1/k_{b2} + 1/k_{s2} + 1/k_{a2}} + \frac{1}{1/k_h + 1/k_{b1} + 1/k_{s1} + 1/k_{a1} + 1/k_{b2} + 1/k_{s2} + 1/k_{a2}} \tag{4}$$

3. Proposed potential energy model to calculate TVMS of misaligned gear shaft including friction

3.1. Effect of shaft misalignment on TVMS of spur gear pair

Shaft misalignment is considered as one of the most common problems in rotating machines, which leads to generate vibrations and extra dynamic loads on transmitting gear teeth. Good alignment for gear shaft means that shafts are parallel