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Active vibration control of a single-stage spur gearbox

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ABSTRACT

The dynamic transmission error between driving and driven gears of a gear mechanism with torsional mode is induced by periodic time-varying mesh stiffness. In this study, to minimize the adverse effect of this time-varying mesh stiffness, a nonlinear controller which adjusts the torque acting on the driving gear is proposed. The basic approach is to modulate the input torque such that it compensates the periodic change in mesh stiffness. It is assumed that gears are assembled with high precision and gearbox is analyzed by a finite element software to calculate the mesh stiffness curve. Thus, change in the mesh stiffness, which is inherently nonlinear, can be predicted and canceled by a feed-forward loop. Then, remaining linear dynamics is controlled by pole placement techniques. Under these premises, it is claimed that any acceleration and velocity profile of the input shaft can be tracked accurately. Thereby, dynamic transmission error is kept to a minimum possible value and a spur gearbox, which does not emit much noise and vibration, is designed.

1. Introduction

Gear is an important mechanical element of many heavy industry machinery. Spur gears, which can transmit rotary motion, torque, and convert speed between parallel shafts, are known to be the simplest type of gears. It is known that operational efficiency of spur gears is much higher than any other gear types. Therefore, the involute gearing has found many applications in industry. Advantage of spur gears with involute profile can be listed as:

- it is simple to change tooth thickness and center distance;
- spur gears can be produced with high precision, and nonstandard involute gears can be produced by using standardized tools,
- change in the center distance of spur gears does not result in transmission error.

When a pair of spur gears is assembled to transmit torque between parallel shafts, prediction of spur gears dynamics is vital to monitor the condition of gears and to control transmission systems. When involute profile of spur gears is manufactured with zero error (e.g. manufacturing tolerance is very tight and there is no load) a pair of spur gears is expected to run with zero transmission error. However, when the same pair of gears is studied under load, the speed of input shaft is transmitted to the output shaft with an error due to the deformation of gear bodies and tooth profile errors.

This problem (e.g. vibration and noise is searched for) is closely related to periodic change in the mesh stiffness; the

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mesh stiffness of a pair of gears changes throughout a typical meshing cycle. Because the number of teeth that come into contact jumps between two integer numbers e.g. for low contact spur gears, it alternates between one and two. This phenomenon, which causes a sudden change in the mesh stiffness, is the fundamental source of excessive vibration and noise. It has been experimentally shown that amplitude of vibration takes large values when the gear mesh frequency is equal to the fundamental natural frequency.

Since periodic time-varying mesh stiffness and the associated transmission error lies at the heart of spur gear dynamics, in the past, this subject has been studied intensively. Most of these efforts have focused on the dynamic analysis of gears: computation of dynamic load that acts on gear teeth, prediction of transmission error, etc. On the other hand, the transmission error between a pair of gears has been investigated by others to minimize its amplitude, because once the amplitude of transmission error is minimized, the amplitude of dynamic load drops to smaller values. For this purpose, involute profile of gears is modified and an even mesh stiffness is sought. However, application of control techniques to gear dynamics is relatively new and few papers have been published so far.

In this study, we propose to use the torque modulation technique to compensate for the change in mesh stiffness. In this respect, it is assumed that full state-measurement is available to a nonlinear controller. Furthermore, it is also assumed that geometry of the gearbox is known with high precision e.g. the starting position of gears. Thus, using this knowledge together with material properties of gears, the mesh stiffness of a pair of gears can be computed as a function of gear's angular position. On the nonlinear controller side, an inverse dynamic model of the gear mechanism is developed to predict nonlinear forces generated by the time-varying periodic mesh stiffness. Once, these nonlinear forces are canceled by a feedforward loop, remaining gear dynamic is linear, so it can be controlled with pole-placement techniques. Hence, it is claimed that any acceleration and/or velocity curve of the input shaft can be tracked accurately.

The main goal of this research is to regulate the speed of an input shaft which drives a spur gear mechanism, eliminate the excessive transmission error between driving and driven gears, and minimize the amplitude of dynamic loads acting on the gear teeth. With this perspective in mind, finite element model of a pair of spur gears is developed and its mesh stiffness is computed in advance of the dynamic analysis. This nonlinear stiffness term is inserted into the mathematical model of a pair of spur gears. Then, under varying loading conditions, dynamic analysis of this transmission system is made when it is controlled by this so-called nonlinear controller. It has been shown that it is possible to regulate the speed of a shaft that powers the driving gear and minimize the amplitude of dynamic transmission error between a pair of gears. Thereby, it has been shown that a gearbox, which does not emit much noise, can be designed.

2. Literature survey

Gear dynamics has many frontiers which displays different characteristics [1,2]; in the first place the model itself is a major concern. Different dynamic models have been developed; in general, these models can be classified as lumped-parameter models, finite element models and continuous systems. Besides this categorization, solution techniques, which solely depend on the model and objective of study, take different forms. Steady-state and transient response analysis requires that different techniques are employed for time-efficient solvers. On the other hand, a major stream of work is recognized for the effects that are included in the model. These effects range from shaft misalignment, profile errors, manufacturing errors, tooth models, time-varying mesh stiffness, beam model of gear tooth, backlash, elasticity of shafts and bearings, etc. On the optimization side, gear tooth profile has been modified to reshape the time-varying mesh stiffness. This type of effort is also recognized as a diversion from the main stream of work on gear dynamics in which the primary interest lies in the dynamics of a pair of gears. Despite the fact that profile modification is a common practice to minimize the change in the amplitude of mesh-stiffness and transmission error, in last decade, active vibration control of gear noise has appeared as a promising approach in the field of gear dynamics. However, few papers in which active vibration control of gears is studied have been published so far.

Dynamic modeling of gears has several aspects: in one direction, lumped-parameter models with less degree-of-freedom (DOF) have been used; on the other hand, complicated models with large DOF have been used to study sophisticated nature of gear dynamics. In this respect, several authors have studied nonlinear gear dynamics with finite element model [3–8].

Discrete-model systems have been used intensively to study gear dynamics as well. In these models, the most distinctive feature of geared systems, the time-varying mesh stiffness is calculated and inserted in the discrete model as a nonlinear spring. These models not only accelerate the speed of simulations but they also open up space for advanced models in which the contribution of supporting elements are included. These models are solved with different mathematical techniques in which the main interest is in the steady-state response of the system, though few authors have attempted to predict the transient response. 1-DOF model with time-varying mesh stiffness was used to study the steady-state response of a pair of low-contact ratio spur gears [9,10]. Multi-mesh transmissions with helical/spur gears were studied [11–13]. Dynamic behavior of a single stage spur gear reducer was studied [14–16].

The sophisticated nature of geared dynamics requires that different effects are included in the mathematical model; backlash and tooth separation, time-varying mesh stiffness, shaft misalignment, bearing deflection. This has led to a diverse model set in gear dynamics literature. The effect of contact ratio on tooth separation was investigated [17]. Dynamic response of spur gears considering translational motion due to bearing deformation was studied [18]. The effect of involute contact ratio was studied [19]. Non-linear vibration of a pair of gears including shaft flexibility was simulated [20]. A