16th INTERNATIONAL CONFERENCE
Dynamical Systems – Theory and Applications
December 6-9, 2021, On-line

Effect of gear mesh stiffness and lubricant nonlinearities on the dynamic response of gear transmission systems

Hamza Mughal*, Nader Dolatabadi, Ramin Rahmani

Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Leicestershire, UK

* Presenting Author

Abstract: Gear dynamic response is the underlying cause of gearbox noise, vibration, and harshness (NVH) in automotive powertrains. Gear whine, a dominant form of gearbox NVH in electric vehicles, is caused by static and dynamic errors induced mainly by the variation in gear mesh stiffness. Therefore, an accurate evaluation of time-varying mesh stiffness (TVMS) is important. A dynamic model of a simple spur gear system is developed using an improved analytical TVMS method combined with a nonlinear Hertzian contact model. The nonlinear stiffness and damping of lubricant under elastohydrodynamic regime of lubrication (EHL) is adapted to investigate NVH performance of the system. Results from literature are used to verify the model. The effect of nonlinearities on the system stability and response are identified.

Keywords: Nonlinear gear dynamics; Time-varying mesh stiffness; Dynamic transmission error; Elastohydrodynamic contact; NVH

1. Introduction

Concerns over the environmental impact of internal combustion (IC) engines have surged the demand for electric vehicles (EVs) in public and private transportation sectors. Hence, automotive manufacturers have focused on development of electric powertrains. Integration of electric machines with conventional transmissions (i.e., gearboxes) raise new concerns associated with powertrain noise, vibration, and harshness (NVH). In an EV, powertrain noise mainly originates from the reducer (gearbox) and electric motor in the form of high order tonal noise at high frequencies, also known as whine noise [1]. This tonal noise can be disconcerting to driver and passengers despite its lower sound pressure levels compared with the IC engine noise.

Whine noise is mainly caused by internal excitations due to the time-varying mesh stiffness (TVMS), dynamic transmission error (DTE) and gear impact inside backlash and clearances [1]. These material and geometrical nonlinearities are combined with the nonlinear behaviour of lubricant during elasto-hydrodynamic regime of lubrication (EHL). Development of a robust dynamic model is paramount to better understanding of the transient nonlinear response of the gears and NVH performance of the power transmission unit.

In this study, a nonlinear load dependent Hertzian contact model combined with a TVMS analytical model based on the potential energy method is adapted to accurately evaluate the meshing stiffness of a spur gear pair set. This TVMS model considers the bending, shear, axial, and the tooth fillet foundation stiffness components. TVMS varies with the number of pairs of teeth in contact and the location of the point of contact on the involute tooth profile. The lubricant stiffness and damping during EHL are evaluated to accurately predict the dynamic response and acoustic emission of the spur gear pair system. Such detailed study of gear dynamics with combined analytical TVMS model and lubricant nonlinear effects has hitherto not been reported in the literature.

2. Results and Discussion

A nonlinear two-degrees-of-freedom dynamic model is developed. The geometrical nonlinearities reside in backlash, possible tooth separation during meshing, and back-side collisions. The basic dynamic models use a square wave meshing stiffness for simplicity. In this study, meshing stiffness is modelled using a detailed analytical TVMS using the concept of potential energy. TVMS nonlinearly varies with number of teeth in contact, position within the line of contact and Hertzian contact stiffness. Lubricant EHL stiffness and damping are initially neglected to verify the dynamic model using the available experimental results from literature [2]. The model is further refined considering lubricant stiffness and nonlinear damping effects as defined in [3]. The effects of geometrical, TVMS and lubricant nonlinearities on the dynamic response, stability and the emitted noise are further investigated. The phase-plane response for the current model is compared with the response of the basic model with constant damping ratio (Figure 1).

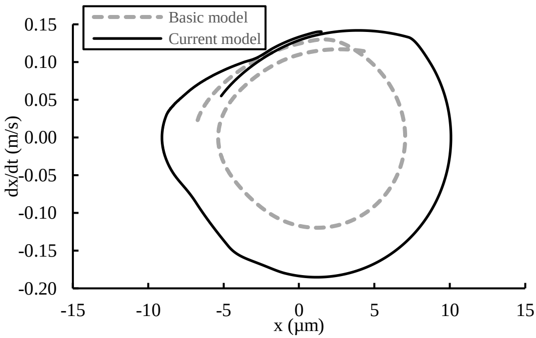

Figure 1: Comparison of phase-plane responses of the TVMS model with nonlinear damping effects and the basic model at 2600 Hz meshing frequency

3. Concluding Remarks

Existence of a reliable analytical TVMS model is essential to the accurate prediction of DTE. Lubricant stiffness and nonlinear damping participate in contact nonlinearity and energy dissipation. The effects of gear body compliance on TVMS have been studied. The effect of nonlinearity originated from the inclusion of the lubricant damping and stiffness is shown and discussed. Poincare and FFT diagrams will further demonstrate the impacts of the nonlinear parameters on the gear set stability and vibrations.

References

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