Mechanism and Machine Theory 96 (2016) 179–191

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

An analytical study of controlling chaotic dynamics in a spur gear system

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ARTICLE INFO

Article history:
Received 21 July 2014
Received in revised form 22 September 2015
Accepted 5 October 2015
Available online 11 November 2015

Keywords:
Gear vibration
Chaotic dynamics
Control

ABSTRACT

In order to design and develop an optimal gear transmission system, it is important to control the occurrence of various types of nonlinear phenomena such as bifurcation and chaotic response. This paper describes a control system for elimination of the chaotic behaviors in a gear dynamic system. Analytical approach concerning the elimination of chaos in a gear system with applying the external control excitation is given by using Melnikov method. The numerical simulations are considered to check the validity of theoretical predictions, and also to investigate the efficiency of the proposed control system to eliminate the homoclinic bifurcation and chaos in nonlinear gear systems.

1. Introduction

Gear systems are known as one of the most important sources of vibration and noise in industrial rotary machinery and power transmission systems. As a consequence, many studies have been performed for the purpose of analyzing gear dynamics. The more accurate evaluations and experimental investigations of the gear dynamic response have indicated some complicated phenomena such as regular vibrations, non-periodic or even chaotic motions on some system parameters. With the development of nonlinear dynamics theories, the nonlinear characteristics of these systems such as stability, periodic responses, bifurcations, and chaotic behaviors, have become the most interesting research areas. For instance, the experimental results, were reported by Kahraman and Blankenship [1], indicated that several nonlinear phenomena such as sub and super-harmonic resonances and chaotic behaviors occur when a spur gear pair with clearance nonlinearity subjected to combined parametric and external forced excitation is present. Also, they [2] had presented a single-degree-freedom gear system involving combined parametric excitation and clearance to analyze the steady state solutions by means of multiple term HBM approach and experimental validation. The IHBM was applied by Raghothama et al. [3] to investigate periodic responses and bifurcations of a nonlinear geared rotor-bearing system with time varying mesh stiffness and backlash. Also, the chaotic response was investigated by using numerical simulation method, and the Lyapunov exponent was calculated.

In [4], a generalized nonlinear time varying dynamic model of a hypoid gear pair with backlash nonlinearity was formulated. Computational results reveal numerous nonlinear behaviors such as sub-harmonic and chaotic responses, especially for lightly loaded and lightly damped cases. Also, Luczko [5] investigated a nonlinear model with the time varying stiffness and backlash to describe vibration of a one-stage gearbox. The possibility of existence of chaotic response was studied using numerical integration and spectrum analysis. The simulation results reveal that the system exhibits a range of quasi periodic or chaotic behaviors. In [6], Wang et al. developed a dynamic model of gear system in which sliding friction force between each tooth pair, backlash and

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http://dx.doi.org/10.1016/j.mechmachtheory.2015.10.002
0094-114X/

time varying mesh stiffness was considered. The complex nonlinear phenomena such as periodic response, chaos and bifurcation in system were investigated numerically.

Chang-Jian et al. [7] investigated dynamic responses of a single-degree-of freedom spur gear system with and without nonlinear suspension and found periodic and chaotic dynamics in this system. In addition, they [8] analyzed dynamics of a gear pair system supported by journal bearings. Nonlinear suspension effect, nonlinear oil film and gear mesh force are also considered. The possibility of existence of periodic, sub-harmonic and chaotic responses for some regions of the parameters were studied using numerical integration.

From the above mentioned references, one finds that non-periodic or chaotic motions have been widely found in nonlinear gear systems. Chaotic motion as unusual and unpredictable behavior has been considered as an undesirable phenomenon in vibrations of a gear system. Though the previous studies investigated the existence of bifurcation and chaos in gear dynamics, there is no attention to control these phenomena. Therefore, in order to design and develop an optimal gear transmission system, it is important to control or eliminate these phenomena.

Chaotic behavior is a very interesting nonlinear phenomenon, and it has been found in a large number of nonlinear science and engineering systems. In general, chaos is an unwanted behavior and as a consequence a major attention has received in recent years, to control and/or eliminate the chaos in these systems. Design and proper choice of system parameters are the basic ideas for suppression or elimination of the chaotic behavior. It is clear that for each parameter, there are some boundaries and limits. Beyond this area is causing serious influence on the system performance and the design is not possible. In such conditions the methods of controlling chaos are proposed. Generally, these methods have been classified in two main groups. First of them is to stabilize a determined unstable periodic orbit which is embedded in a chaotic attractor, usually achieved by the use of feedback control method [9–14]. Second is to eliminate the chaotic behaviors by applying an additional periodic excitation force or by perturbing a system parameter with small harmonic identified as non-feedback control method [15–21]. To control a determined unstable periodic orbit by feedback control methods, the OGY control approach being the most representative was introduced by Ott, Grebogi and Yorke [22]. This method does not require the information of the system equations, but one must determine the unstable periodic orbits and require performing several calculations to create the control signal. The feedback control methods seem to be efficient but have some difficulties in practical experiments.

In such cases, non-feedback control methods might be more useful and can be easily realized in practical experiments. There are numerous experimental and numerical examples of converting chaos to a periodic motion by applying an additional excitation force or by perturbing a system parameter. This method requires information of the system equations to create control forces. It does not require continuous tracking of the system state, and also, it is more robust to noise.

The main objective of this study is to develop a practical model of gear system for controlling and suppressing the chaotic behavior. To this end, a nonlinear dynamic model of a spur gear pair with backlash and static transmission error often investigated in the literature [23–25], is formulated. Non-feedback control method is used to control chaos by applying an additional excitation torque to the driver gear. The parameter space regions of the control excitation where homoclinic chaos can be eliminated are obtained analytically by generalization of Melnikov approach, which is one of the few analytical methods to study the occurrence of homoclinic bifurcation and transition to chaotic behavior in the nonlinear systems [25–33].

The organization of the paper is as follows. In Section 2, a nonlinear dynamic model of a spur gear pair including the backlash and static transmission error is formulated. The analyzing of the unperturbed system and the conditions for existence of chaotic behavior in terms of homoclinic bifurcation by using Melnikov analysis are performed in Section 3. In Section 4, the control model is described. The parameter space regions of the control excitation for elimination of chaos are investigated. In Section 5, numerical simulation results are performed to verify the theoretical analysis and show effectiveness of the proposed control system. Finally, the conclusions are presented in Section 6.

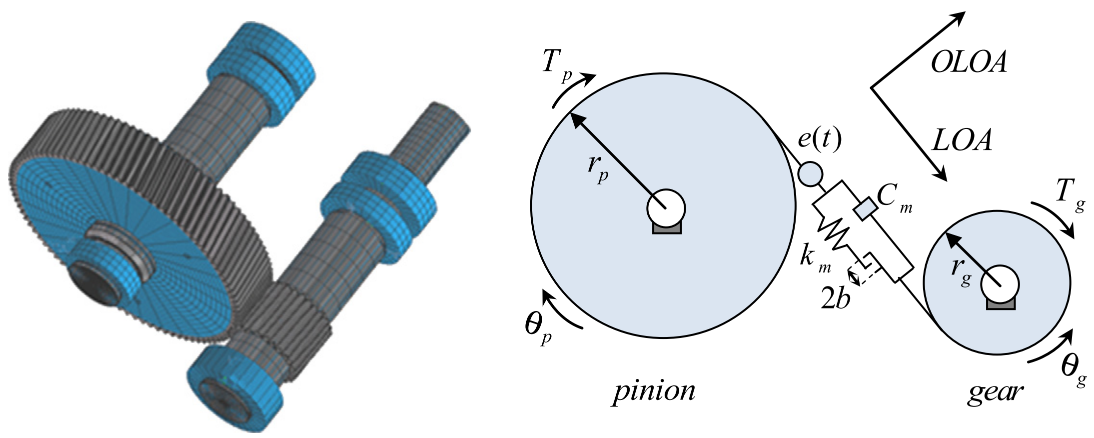

Fig. 1. Schematic of the gear model.