Journal of Sound and Vibration ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Friction-induced noise of gear system with lead screw and nut: Mode-coupling instability

Jaeyoung Kang

Division of Mechanical and Automotive Engineering, College of Engineering Kongju National University, Cheonan-Si, Republic of Korea

ARTICLE INFO

Article history:
Received 22 January 2015
Received in revised form
10 June 2015
Accepted 4 July 2015
Handling editor L.G. Tham

ABSTRACT

The mode-coupling instability in the gear system with a lead screw and nut is investigated. The actual gear geometry and the contact kinematics are developed in analytical the model. The complete set of vibration modes including axial, torsion and transverse displacements is applied to seek the solution of the linearized gear system. From the linear stability analysis, the bending mode pair as well as the torsion and axial mode pair have the strong tendency towards the mode-coupling instability. It points out that squeak noise in the lead screw system can occur even for a constant friction coefficient without the negative-friction velocity slope. The closed-form solution and numerical calculation also show that the rotating direction can drastically change the onset of mode-coupling instability.

1. Introduction

Noise and vibration is the typical problem generated in the mechanical gear system. The excitation at the gear teeth and the ensuing noise in gear system was broadly investigated through the numerical and experimental methods over the several decades [1,2]. Unfortunately, the numerical analysis for friction noise during the operation of gear system has not been performed by the finite element method even though loud gear squeak was often observed in the various gear systems such as a platform, test machines and automotive seat system. The numerical modeling for gear friction noise requires the angle-varying contact stress distribution, the description of the perturbed dynamic motion and the ensuing contact stress variation on the gear tooth contact at the quasi-static angle configuration. This task seems quite complicated for the typical gear system, but some numerical work on friction noise has been conducted by the commercial finite element software in the simpler contact applications.

The friction noise is induced by the self-excited vibration in the friction-engaged system. Friction stress variation due to vibration produces non-conservative work leading to the linear instability of the system. From the linear stability theory, the onset of friction noise is determined by the positive real parts of eigenvalues in the linearized equations of motion. The modeling of the friction-induced noise problem in literature has been limited to some mechanical applications such as automotive brake squeal [3,4] and hip squeak [5] by use of the commercial finite element software. In fact, the finite element simulation on the complex eigenvalue analysis often requires enormous computing time even for a single system configuration which impedes the progress of analysis. For providing the insight over the causing mechanism and the effective sensitivity analysis, the simplified mathematical models with spring-mass [6,7] or continuous elements [8–10]

E-mail address: jkang@kongju.ac.kr

http://dx.doi.org/10.1016/j.jsv.2015.07.002
0022-460X/

Please cite this article as: J. Kang, Friction-induced noise of gear system with lead screw and nut: Mode-coupling instability, *Journal of Sound and Vibration* (2015), http://dx.doi.org/10.1016/j.jsv.2015.07.002

were proposed. Particularly, the major mechanisms causing the onset of friction noise was found to be the mode-coupling and the negative friction–velocity slope [11].

Due to the complex geometry and the highly nonlinear characteristics of the gear system, the numerical finite element approach for the squeak noise of the actual gear geometry was not developed. Instead, the simplified lumped-mass model was proposed to correlate the experimental results. Gallina et al. [12,13] proposed a 2dof model of the screw-jack system where the asymmetric inertia matrix of the torsion and axial displacements made the system unstable. Vahid et al. [14] simplified the lead screw and nut components of an automotive seat adjuster as a 4dof lumped-mass model and pointed out that the torsion mode of the lead screw became unstable by the negative friction–velocity slope mechanism. Kang et al. [15] modeled the lead screw–nut system to be a vibrating circular beam subject to friction stress over the actual contact thread and showed that the negative friction–velocity curve generated the dynamical instability due to the bending modes of the lead screw. Due to the over-simplification, however, friction stress variation essential for the mode-coupling mechanism in the lead screw system was missing. Besides, the previous negative friction-slope models [14,15] failed to explain Olofsson's results [16] where the instability of bending modes was highly dependent on the nut location. Therefore, the remaining task is now to develop the lead screw gear model demonstrating the mode-coupling type instability and explaining the dependency of the nut location on the occurrence of squeak noise.

For the non-conformal contact gear system such as the spur and helical gear, the finite element method has provided the time-varying mesh stiffness on the gear tooth pair [17–19]. The time-varying gear mesh stiffness is essential in modeling single-tooth contact on the tooth pair in the nonlinear dynamic transient analysis. For determining the linear modal characteristics of the gear system, the constant mesh stiffness at the quasi-static equilibrium is used [20,21]. In the present paper, contact over the thread between thread pair of the screw and nut is assumed to be conformal in the contact modeling of the lead screw–nut system. Contact stiffness over the contact thread area is newly introduced as the constant gear mesh stiffness per unit area. One major advantage of the contact stiffness modeling is to realize the contact normal and friction stress variation which is essential for friction-coupling among the system modes leading to the mode-coupling instability [11].

First, the lead screw–nut model subject to friction contact on the thread is developed with the system vibration modes. With the full-mode model, the dynamic instability of the gear system is shown to be possible without the friction–velocity slope. Particularly, the nut constrains the motion of the lead screw so that the local constraint due to the nut location changes the system frequencies and mode shapes. The squeak propensity with the nut location is investigated through the eigenvalue sensitivity analysis and mode shape visualization.

Then, the propensity of the mode-coupling type instability is investigated by the two-mode models of the torsion/axial mode pair and the bending mode pair without loss of generality. Particularly, it is also proven that the propensity of the mode-coupling instability in the torsion/axial mode pair can be estimated from only tooth topology.

2. Modeling

The rotation of the lead screw makes the nut move in the axial direction where the nut normally carries an weight as shown in Fig. 1. During operation, contact forces act on the contact thread between the screw and nut. Their direction vectors at a contact point are defined as in Fig. 2. The following notations are used for the description of the lead screw system: rotating speed (Ω), effective radius of screw (R), helix angle (β), half of thread angle (γ), axial load (F_z), nut length (b) and its location (z_o). In the model, the positivity of Ω determines the direction of rotation in such a way that a positive value of Ω represents the forward rotation in Fig. 3. It is assumed that the contact stiffness per unit area (k_c) is uniformly distributed over the contact thread as illustrated in Fig. 3. Contact stress acting on the thread is also assumed to be uniformly distributed over the contact side of the section $a-a'$ (Fig. 2b) so that the contact kinematics at c (Fig. 3) is used for the description of the contact stress variation on the contact thread. For the bending mode, the Bernoulli–Euler beam theory is applied in the analysis [22].

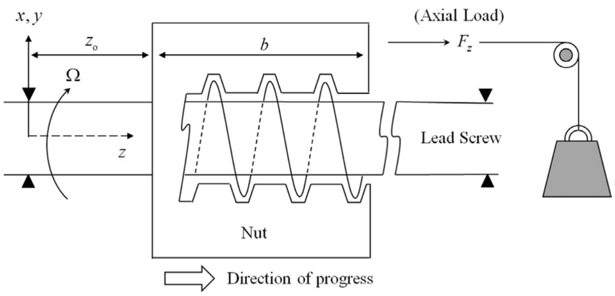

Fig. 1. Configuration of the lead screw system for forward rotation.

Please cite this article as: J. Kang, Friction-induced noise of gear system with lead screw and nut: Mode-coupling instability, *Journal of Sound and Vibration* (2015), http://dx.doi.org/10.1016/j.jsv.2015.07.002