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Impact of an irregular friction formulation on dynamics of a minimal model for brake squeal ☆

Merten Stender [a,*], Merten Tiedemann [b], Norbert Hoffmann [c,a], Sebastian Oberst [d,a]

[a] Hamburg University of Technology, Dynamics Group, Schlossmühlendamm 30, 21073 Hamburg, Germany
[b] AUDI AG, 8045 Ingolstadt, Germany
[c] Imperial College London, Department of Mechanical Engineering, London SW72AZ, United Kingdom
[d] University of Technology Sydney, Centre for Audio, Acoustics and Vibration, Sydney, NSW 2007, Australia

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ABSTRACT

Friction-induced vibrations are of major concern in the design of reliable, efficient and comfortable technical systems. Well-known examples for systems susceptible to self-excitation can be found in fluid structure interaction, disk brake squeal, rotor dynamics, hip implants noise and many more. While damping elements and amplitude reduction are well-understood in linear systems, nonlinear systems and especially self-excited dynamics still constitute a challenge for damping element design. Additionally, complex dynamical systems exhibit deterministic chaotic cores which add severe sensitivity to initial conditions to the system response. Especially the complex friction interface dynamics remain a challenging task for measurements and modeling. Today, mostly simple and regular friction models are investigated in the field of self-excited brake system vibrations. This work aims at investigating the effect of high-frequency irregular interface dynamics on the nonlinear dynamical response of a self-excited structure. Special focus is put on the characterization of the system response time series.

A low-dimensional minimal model is studied which features self-excitation, gyroscopic effects and friction-induced damping. Additionally, the employed friction formulation exhibits temperature as inner variable and superposed chaotic fluctuations governed by a Lorenz attractor. The time scale of the irregular fluctuations is chosen one order smaller than the overall system dynamics. The influence of those fluctuations on the structural response is studied in various ways, i.e. in time domain and by means of recurrence analysis. The separate time scales are studied in detail and regimes of dynamic interactions are identified. The results of the irregular friction formulation indicate dynamic interactions on multiple time scales, which trigger larger vibration amplitudes as compared to regular friction formulations conventionally studied in the field of friction-induced vibrations.

1. Introduction

Friction-induced oscillations have been investigated in numerous fields of research, such as earth quake dynamics [1], fluid-structure interaction [2], and brake squeal [3]. Friction is a multiscale and complex process that involves - among other factors - multiple mechanical forces, chemical interactions, change of surface topology and wear. This complex process leads

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* Corresponding author.
E-mail address: m.stender@tuhh.de (M. Stender).

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to a macroscopic coefficient of friction which has yet not been able to be modeled in full extend. The horizon of dynamic friction description is spanned by on the one hand a fully stochastic and on the other hand a highly nonlinear deterministic approach [4–6]. Depending on the specific frictional contact, one of the latter extremes or a combination of both may be favored for description and modeling. In the automotive industry disk brake squeal is of major concern as it causes significant development and warranty costs. Brake squeal is mostly considered as a tonal noise dominated by a single frequency plus its higher harmonics. Correspondingly, in the majority of research activities brake squeal is treated as regular motion of a mechanical system on a limit cycle [7,8]. This point of view considers only weak nonlinearities and a single time scale in contrast to other research fields such as fluid mechanics. Consequently, friction-induced vibrations of braking systems are often analyzed using linear methods based on spectral analysis and brake models are commonly characterized by modal stiffness or damping parameters. Today, the brake system is typically modeled by either minimal models (investigating the excitation mechanisms) or large FE models (mostly for deriving linear instability regions). Both approaches incorporate simplified friction models which are either static (e.g. Coulomb friction) or velocity-dependent (e.g. Stribeck-type models). Either way the models display merely regular friction. However, recent investigations have revealed signs of deterministic chaos in vibration data gathered from analytical models, laboratory experiments and commercial automotive disk brakes. Gdaniec et al. [9] showed that a rate-dependent friction model suffices for driving a single degree of freedom oscillator into chaotic regimes for specific parameter regimes. Pilipchuk et al. [10] and Olejnik et al. [11] investigated the effect of decreasing velocity on the structural dynamics and damping of an experimental belt-spring-block setup. It was observed that for the majority of belt velocities the dynamic behavior is harmonic while there also exist small epochs of irregular vibrations especially at lower relative velocities. Wernitz and Hoffmann [12] observed low-dimensional irregular dynamics of a brake system in the non-squealing, i.e. steady-sliding configuration. These authors traced back the irregularity to high-frequency interface dynamics on a significantly faster time scale than the audible squeal event. Oberst and Lai [13,14] applied methods from recurrence analysis to show the determinism in the squealing configuration and reconstructed low-dimensional attractors as well as several routes to chaos.

The goal of this investigation is to qualitatively illustrate the effects of irregular interface dynamics on the overall system response of a minimal disk brake model. Thus, in this work the interface dynamics are described by a dynamic friction coefficient that fluctuates according to the low-dimensional chaotic Lorenz attractor. The time scales are chosen such that the interface dynamics act on a one order of magnitude smaller time scale than the mechanical structure. The time series gathered from time integration are characterized by standard methods in time domain and advanced methods from recurrence plot analysis.

Firstly, the mechanical minimal model, the dynamic friction formulation and the superposed irregular fluctuations are introduced. Then, different methods for characterizing a time series are reviewed shortly. Time series of different model configurations are investigated to identify regimes of time scale separation and interaction.

2. Models and methods

A minimal model is chosen to capture relevant physical effects and mechanisms without introducing extensive modeling and computation effort. Thus, this study does not strive to model a friction brake in detail but depict key effects that have been observed experimentally. Accordingly, the parameter values are chosen such that the effects strived after become visible. The minimal model allows to study each separate effect in detail and draw conclusions from analytical considerations. The employed model is built up stepwise: First, a well-known minimal model of a friction brake is introduced. The second step describes the introduction of a dynamic and temperature-dependent friction coefficient before additional irregular fluctuations of the friction coefficient are introduced.

2.1. Disk brake minimal model

The well-known disk model proposed by von Wagner et al. [15] is employed as mechanical structure for the investigation. This model captures the salient features of a disk brake as depicted in Fig. 1. A detailed description of the setup and the kinematics of the model can be found in [15]. Essentially, the central spherical support of the rigid disk (thickness h, central moments of inertia Θ, Φ) allows wobbling motion in the direction of the generalized cardan angles q_1, q_2 while the disk rotates with constant angular velocity Ω. The rotational stiffness k_t and damper d_t create a restoring force when the disk is deflected in either coordinate direction. The frictional point contact is established at radius r by idealized massless pads on either side of the disk. The pads are guided and can only perform motion in the vertical direction. The pad restoring forces are described by a nonlinear (quadratic) stiffness k_{NL} and linear viscous damping d as introduced by Gräbner [16]. The pads are preloaded by normal load N_0 to guarantee contact in equilibrium. Due to the turning disk this model exhibits gyroscopic effects (not related to any energy dissipation) and friction-induced damping. Furthermore, the system is prone to self-excitation which can be traced back to the asymmetry of the displacement proportional coupling terms in the equations of motion (cp. Eq. (4)). In the regime of the linearly unstable equilibrium solution the vibrational amplitudes are limited due to the nonlinear characteristic of the pads: a stable limit cycle exists for the wobbling disk minimal model.