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Friction-Induced Noise and Vibrations: Diagnosis and Prognosis

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Introduction

Friction-Induced noise & vibration problem, such as Squeak & Rattle, belt noise and brake noise, has been one of most challenging technical problems faced by automotive industry. For instance, in North America, up to one 100 million dollars every year are spent on noise and vibration issues in warranty work of automotive brake systems [1,2]. The prediction and control of friction-induced noise and vibrations have been considered as an elusive problem. In this article, the friction-induced noise and vibration problem is reviewed by using brake noise as an example. The time-varying, strong nonlinear and stochastic nature of the problem is emphasized. The new perspective of diagnosis and prognosis are proposed to address this problem. The framework of diagnosis and prognosis could be developed by using nonlinear signal processing, phase space reconstruction, nonlinear stochastic system identification, and statistical pattern recognition, which effectively and efficiently helps identify system, validate numerical model, predict troublesome event occurrence and estimate uncertainty.

Historic Perspectives: The Example of Brake Noise

In automotive industry, friction-induced noise and vibrations have been a critical cost factor because of customer dissatisfaction. Even though several decades efforts were made, friction-induced noise and vibrations still remains surprisingly unpredictable and poorly understood [3,4]. There are many unique dynamic phenomena and underlying mechanisms associated with friction-induced noise and vibrations. The most prominent ones could be listed as follows: stick-slip due to difference between static and dynamic frictions; self-excited vibrations due to velocity-dependent friction; modal couplings; non-smoothness effects; transient contact separation or vibro-impact effects; random excitation; impulsive excitation, sprag-slip; complex vibrations due to complicated friction laws such as rate-dependent friction; parametric vibrations of system with variable normal force and friction; instability due to gyro-effects; vibrations due to nonlinear properties such as nonlinear contact stiffness; time-varying effects due to radical interface change such material generation and removal; uncertainty such as interface wear; combinations and interaction of varied mechanisms. In general sense, friction-induced noise and vibrations have time-varying, nonlinear stochastic features.

As an example, in automotive brake industry, extremely costly trial-and-error troubleshooting process has been applied for brake NVH problems, despite that the numerical modeling and experiments are widely conducted. Over the years, friction-induced vibration and noise in automotive brake system have been given various names in terms of the pattern of the vibration and noise generated such as moan, groan, judder, squeak, squeal, and wire brush, just to name a few. A simple description or classification is to classify the brake vibration and noise to be low frequency vibration/noise, low frequency squeals and high frequency squeals, respectively distinguished by frequency of 1 kHz, and the natural frequency of first circumferential mode of the rotor (roughly 3-4 kHz). The low frequency vibration and noise mainly consists of judder, groan and moan, etc. This category of vibration and noise is mainly caused by friction material excitation, and the energy is transmitted as a vibration response through the brake corner and couples with other chassis components. The squeal is an annoying, high-pitched noise usually close to a pure tone. Low frequency squeal is generally classified as the squeal having a narrow frequency bandwidth in the frequency range above 1000 Hz yet below the first circumferential mode of the rotor. The high frequency brake squeal is defined as noise which contains the first circumferential mode of the rotor, which is produced by friction induced excitation, usually involves in coupled mode resonances with squeal occurring at frequencies above 5 kHz. One of the most troublesome brake noises is high frequency brake squeal. The primary objectives of the research on brake noise can be categorized as: (i) characterization of brake vibration and noise mechanisms using order reduced models, (ii) numerical analysis and prediction of troublesome noise and vibrations; (iii) experimental investigations uses test platform or real systems (iv) trouble shooting of the root cause and corrective action. While some contents of the objectives have been addressed comprehensively in the literature, work on the diagnosis and prognosis is lacking. There are a lot of literatures on automotive disk brake noise and vibrations. The existing reviews conducted in the last three decades years provide a comprehensive source of information [5-14]. Most research has been directed to either analytical and experimental studies of brake noise mechanisms or the prediction of brake noise propensity using finite element methods. Investigation into brake squeal has been conducted by various experimental and analytic methods [15-24]. Experimental methods, for all their advantages, are expensive mainly due to hardware cost and long turnaround time for design iterations. Frequently discoveries made on a particular type of brakes or on a particular type of vehicles are not transferable to other types of brakes. Product development is frequently carried out on a trial-and-error basis. There is also a limitation on the feasibility of the hardware implementation of ideas. A quietness margin for robust design is usually not found experimentally. Analytical or numerical modeling can simulate different structures, material compositions, operational and environmental conditions of brakes. With these methods, noise performance and improvement measures can be examined conceptually before a prototype is made and tested. Theoretical results can also provide guidance to an experimental set-up and help interpret experimental findings. The conventional numerical methods consist of complex eigenvalue analysis in the frequency domain and transient nonlinear analysis in the time domain. The complex eigenvalue analysis may over-predict or under-predict the number of unstable vibration modes and not all predicted unstable

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vibration modes will result in troublesome noise. These could be attributed to the inherently high sensitivity of the friction-induced vibration problem to the variation or the small changes of parameters, the uncertainty of the structure, materials and friction parameters, and the unforeseen effects of micro-level interface evaluations on friction. Brake components possess a large range of variations in material properties and sizes. The influence of the variations can be seen from measured and simulated frequencies on system and component levels. The variations present great difficulties in validating a numerical model or a physical design. A robust theoretical model taking into consideration the uncertainties due to material and size variations is needed. It is noted that the repeatability of friction tests and brake noise tests is notoriously poor. Brake noise is a largely elusive phenomenon, partly due to the stochastic features of friction and the relevant time-varying factors such as interface profile, wear, interface films. The theoretical stochastic models have been developed to address variability and uncertainty in brakes noise [25-34]. A typical study is reported in [26], which documented a robust design of a disc brake through structural optimization using the complex eigenvalue approach, considering the variation of friction coefficient, major elastic constants and the effect of material worn-off. The evaluation of robustness can be conducted using commercial available software to give varied statistical measures [29]. [30,31] explores the sensitivity and uncertainty of predictions from a dynamics modal point of view. A method for efficiently estimating prediction error bounds is presented and validated using representative parametric uncertainties. It is illustrated that physical effects such as contact stiffness, damping and friction laws can to extreme sensitivity. In [32], a design of experiments study of brake noise is presented. The experimental results were analyzed using statistical methods including correlation analysis, semblance analysis and joint recurrence quantification analysis. These results highlight the nonlinear character of brake squeal and indicate the potential of using nonlinear statistical analysis tools to analyze disc brake squeal. In [33], neural network method is used to predict disc brake performance. In [34], polynomial chaos expansions approach is used to tackle with stochastic eigenvalue problems with applications to linear stability calculations for a simplified brake system in which the stability of a finite element model of a brake is investigated when its friction coefficient or the contact stiffness are modeled as random parameters. Results are compared to Monte Carlo simulations. The analysis of brake noise propensity is primarily based on linear approaches. On the other hand, it has been recognized that the brake noise and vibration involves a number of nonlinear phenomena such as bifurcation and chaos [35-42]. It is estimated that the onset of squeal happens in linear conditions and that nonlinearity defines the envelope of the vibration amplitudes. The nonlinear models are necessary to estimate the vibration amplitude after the onset of squeal, and predict the complex modes and interactions. The transient nonlinear analysis is time-consuming and has the difficulty of interpretations. How to include nonlinearity in the prediction of brake squeal propensity remains a challenge. In [38], test data obtained from a full brake system is investigated and the chaotic structures of noisy data from the squealing events are characterized by using recurrence plots. The lower dimensional attractors are quantified by Lyapunov exponents. In [40], brake vibration data up to ultrasonic regime is investigated using recurrence analysis and phase space reconstruction. It indicates that irregular vibration states of friction brakes are strongly dominated by intermittency phenomena which are dominated by low-dimensional irregular deterministic dynamics rather than by high-dimensional stochastic processes. In [42], the investigation shows the complexity of the contributions of different harmonic components in transient friction-induced vibrations with the coexistence of multi-unstable modes. Besides fundamental resonance, certain additional unstable mode can appear which is not predicted by the complex eigenvalues analysis. Besides numerical analysis, extensive testing of brake noise on dynamometers is required in order to ensure that the noise performance of brakes is acceptable. Particular, the ability of the complex eigenvalue method to predict brake squeal propensity is limited, the numerical analysis in practice needs to be supplemented by extensive dynamometer tests. Both theoretical methods and experimental methods are needed to capture the underlying physics. These methods remain indispensable tools for understanding brake noise and for achieving improvements on noise performance [43-47]. Despite several decades' research and a lot of progress being made, the underlying mechanisms of noise and vibration generation are still not fully understood. The efficient and effective methodology for the prediction of brake noise has still been unavailable, and the trial-and-error based simple correlations of numerical modeling and test data has still been the major method for brake noise analysis and prediction in automotive industry. Even though there is lot of researches on modeling, numerical simulation and experiments as well as qualitative correlation and approximate model updating based on linear modal analysis theory, there are rare existing work for model verification and validation with mathematical rigor. For instance, there has been a lacking of the research on the critical aspects such as nonlinear system identification, stochastic system identification and nonlinear stochastic system identification of brake noise and vibration.

Diagnosis and Prognosis

Diagnosis is the early detection of faults in complex nonlinear stochastic systems, the classification and the identification of the root causes of faults. On the other hand, prognosis is to predict the propensity of fault initiation and the evolution of the fault occurrence conditions and to estimate the uncertainty. The prognostics and health management and health monitoring technology have been fully developed by the professional community of electronics, aerospace and civil engineering [48,49]. In [50-56], a framework of diagnosis and prognosis has been implemented and developed for contact/friction-induced vibrations of near contact slider in hard disk drive system.

The similar technology can be applied to tackle with friction-induced friction and noise problems in automotive systems. The diagnosis and prognosis framework could be developed for efficient and effective prediction of brake noise and vibrations due to its nonlinear and stochastic natures. Existing methods for brake noise troubleshooting and prediction tend to be linear analysis and modal testing-centric. These often fail to provide correct predictions due to the neglect of the following inherent characteristics of friction-induced vibrations: complex time-varying, nonlinear stochastic phenomena; high sensitivity of friction-induced vibrations to small changes in parameters; unavoidable variability and uncertainty of geometry/material/structures; and the significant effect of the unpredictable small-scale property's evolutions on the macro-scale dynamical phenomena. The existing nonlinear and stochastic analysis on brake noise and vibrations has been in infancy stage. The development of a diagnosis and prognosis offers solutions to overcome these limitations by comprehensively dealing with brake noise and vibration problem using nonlinear signal processing, phase space reconstruction, nonlinear stochastic system identification in the context of computational intelligence techniques. A hierarchical multi-levels strategy could be used in the diagnosis and prognosis. In a streamline process, the measured vibration and noise signal could be processed by using nonlinear signal processing approaches to characterize specific nonlinear and non-stationary vibration features, and then the measured signal could be evaluated to extract possible chaotic properties and to characterize random behavior by using phase reconstruction and recurrence analysis. The nonlinear stochastic identifications could be subsequently followed by using measured signal, numerical model and order-reduced models. These elements help capture the dynamics and tribological essentials of the brake system for reliable prediction. Statistical pattern recognition algorithms could be finally used to integrate the above elements and the data sets/knowledge accumulated in previous practice. This is expected to develop a combination of data-driven, physics model-based and knowledge-based diagnostic and prognostic algorithms for automotive brake noise and vibrations, thus offers an unprecedented opportunity to fix brake noise and vibration problems effectively and efficiently for performance improvement.

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