Journal of Sound and Vibration 377 (2016) 106–122

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

A new instability index for unstable mode selection in squeal prediction by complex eigenvalue analysis

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ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form
8 April 2016
Accepted 1 May 2016
Handling Editor: L.N. Virgin
Available online 24 May 2016

Keywords:
Friction-induced vibrations
Energy balance
Contact dynamics
Mode coupling instabilities
Instability index
Brake squeal

ABSTRACT

During these last decades the modal instability of systems, generated by frictional contact forces, has been the subject of a huge amount of works in friction induced vibration literature. Linear and nonlinear numerical analyses have been largely investigated to predict and reproduce squeal vibrations. While nonlinear transient analysis needs large computational efforts, results of Complex Eigenvalue Analysis (CEA) suffer from an over-prediction issue and it is not able to predict correctly the mode that will become effectively unstable in case of several unstable eigenvalues. Because the CEA has been adopted as an efficient tool for brake design, a more reliable index is here proposed, from the CEA outputs and energetic considerations, to identify the mode that will become effectively unstable. A modular lumped model is developed to reproduce friction induced vibrations. The use of the eigenvalue real part, as discriminant of the system instability, is here combined with information coming from the eigenvectors, projected on the equilibrium position, to account for the energy flows involved in the squeal phenomena. This approach allows to define a Modal Absorption Index (MAI). The MAI allows for comparing unstable modes of the same system and is applied in this paper to predict, by CEA outputs, the unstable mode that will effectively result in squeal vibrations.

1. Introduction

In the analysis of Friction-Induced Vibrations (FIV) issues [1], particular emphasis has been dedicated to the unstable vibrations [2,3]. In fact, the severe operating conditions generated by this phenomena on the mechanical systems, i.e. the high amplitude vibrations often associated to noisy sound emissions, tickled, for instance, the research on the brake squeal [4,5] and on the hip endoprosthesis squeaking [6,7].

This unstable behavior was originally attributed to a discrete or continuous variation of the friction coefficient with speed (velocity-slope) [8,9]. Nowadays the idea, initially proposed by Spurr [10], that the instability can be "geometrically induced"

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http://dx.doi.org/10.1016/j.jsv.2016.05.002

and can be reached also with a constant friction coefficient is currently accepted. Hence, the friction force can be expressed as a follower force [11] and friction-induced vibrations are in this case very similar, from a mathematical point of view, to the flow-induced vibrations and to the flutter instability [12].

In this framework the Complex Eigenvalue Analysis (CEA) represents a fundamental tool to evaluate the stability of a mechanical system with frictional contacts, and this approach is widely used in the design and optimization process of brake systems, to avoid or at least reduce the squeal occurrence. Nevertheless, results from CEA provide an over-prediction of the possible unstable modes, and it is currently impossible to predict which one of the possible unstable modes will actually dominate the transient behavior.

Even if nonlinear semi-analytic approaches allow to reproduce the transient behavior (i.e. amplitude of vibration) of reduced order and simplified models, in case of a single unstable mode of the system [13,14], a full model transient analysis is required in case of multi-instabilities predicted by the CEA [15–17] to find the mode that is actually excited and the amplitude of the limit-cycle vibration.

Recently, energy approaches have been developed to evaluate the "feed-in" energy in unstable friction-induced vibrations [18,19]. For the first time, not only the eigenvalue information but also the eigenvectors, resulting from the CEA, are used to evaluate the capability of each unstable mode to inject energy from the contact interface into the bulk of the system, as an additional information to the propensity for the instability.

In this paper a new instability index, the Modal Absorption Index (MAI) is defined; the main advantage of the new index is the possibility of comparing the capability of each unstable mode of the system to absorb energy from the contact interface; where a multi-instabilities configuration is predicted by the CEA, the new index allows for predicting the unstable mode selection occurring in the transient response of the mechanical system. The comparison between several modes was made possible by the projection of the static equilibrium position on the complex modal base. By this way it is possible to estimate the actual energy absorption due to the wide-band excitation generated at the frictional contact. Similar approaches are used in the seismic analysis of civil structures to evaluate the significance of the vibration modes, i.e. the capability of each mode to be excited by a base excitation [20].

In this paper a modular lumped model is developed to reproduce the friction-induced vibrations. The use of a lumped model allows for a fast integration of the transient solution. The performance of this new instability index has been verified for different system configurations and several operating conditions, showing a good agreement between the predicted (by the MAI index from CEA) and the simulated (by transient analysis) unstable behavior.

2. Mechanical system and numerical tools

2.1. A periodic modular lumped model

A lumped model (LM) composed of masses m connected by springs k and viscous dampers c has been developed to study the friction-induced vibrations on a simple mechanical system (cf. Fig. 1). The model is composed of both masses that are in frictional contact with rigid sliders and masses that are not in contact with the sliders, but linked to the adjacent masses.

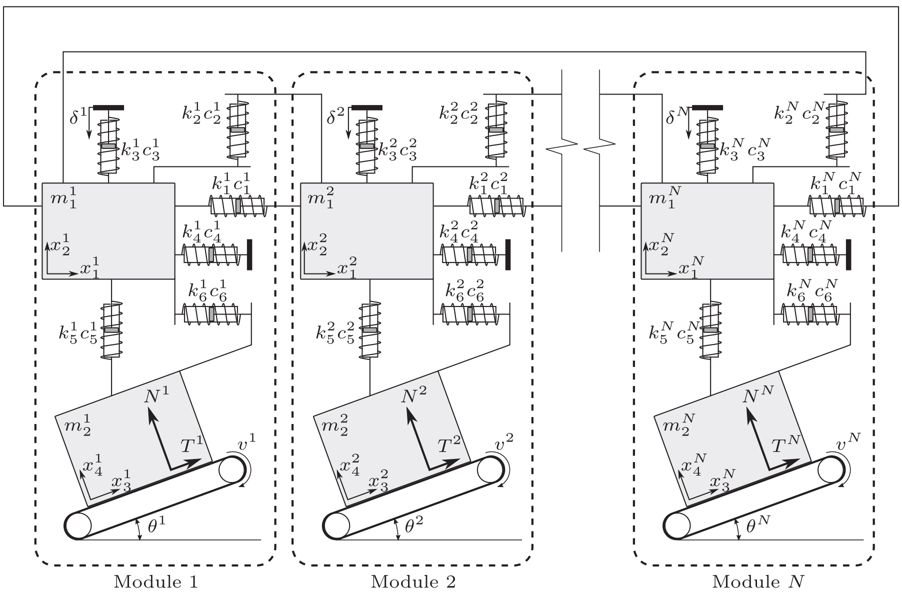

Fig. 1. Periodic and N-modular lumped system.