Mechanical Systems and Signal Processing 41 (2013) 433–453

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

An investigation of the effects of traffic induced local dynamics on global damping estimates using operational modal analysis

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ARTICLE INFO

Article history:
Received 11 February 2013
Received in revised form
21 May 2013
Accepted 19 July 2013
Available online 12 August 2013

Keywords:
Frequency domain decomposition
Operational modal analysis
Damping estimation
Traffic loading
Finite element model
Moving mass

ABSTRACT

Simulations of estimating the modal damping on a bridge from hour-long records of traffic loading were conducted by combining physics-based finite element modeling and signal processing. The finite element method was used to model a bridge consisting of a series of stringer beams resting atop a larger girder. The traffic loads were separated into trains and cars, with the trains modeled as partially distributed moving masses traveling along the girder and the cars modeled as point loads moving along the stringers. From the acceleration time histories, different operational modal analysis (OMA) techniques were used to find estimates for the modal coefficients of damping. The results demonstrated that a quasi-periodic component in the traffic loading introduces significant error to the damping estimates. This error could be observed in the distortion of the peaks for the power spectral densities (PSD) generated from the responses to the traffic simulations. The main OMA technique explored for the damping estimates was Enhanced Frequency Domain Decomposition (EFDD), but it could not compensate or correct for any alterations to the PSD. Other techniques such as the Stochastic Subspace Identification (SSID) method and curve-fitting frequency domain analysis were evaluated, but they produced comparable damping ratio estimates to EFDD and similarly resulted in large errors for the distorted modes. The influence of quasi-periodic loads was perceptible, which means that for certain cases, the nature of traffic loads may result in damping estimates that are considerably inaccurate no matter what OMA technique is chosen.

1. Introduction

Knowing the extent of damping present in structures such as tall buildings and long span bridges is of great importance because of the benefits of energy dissipation, the reduction of response due to seismic loading and the general reduction of excessive vibration. Structural damping can neither often be easily and reliably measured from collected sample data nor can it be simply derived from an analytical formula. As a result, the improved precision of damping estimation has become an important objective within the field of system identification. System identification techniques frequently rely upon output-only models that force the user to make assumptions about the input, most commonly that the ambient forcing function is a broad-band stationary process. This assumption, while mathematically convenient, may not be true in some common cases. When cars and trains travel over a bridge they often do so within a certain range of velocities or at repeated frequencies, meaning that the traffic excitation is not broad-band in its truest sense.

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0888-3270/$ - see front matter
http://dx.doi.org/10.1016/j.ymssp.2013.07.013

Simulating the traffic excitation along a bridge may be modeled by simplifying the problem to moving loads and masses traveling across beams. The response of a beam to a moving load was first addressed by Timoshenko [1] and Jeffcott [2], and the initial analysis was expanded to a two-span beam by Ayre et al. [3]. Consideration was later given to the problem of moving masses traveling across a beam by Stanišić [4,5] who compared a moving force and a moving mass to show the differences in the response of a simply supported beam. Sadiku and Leipholz [6] demonstrated that a moving force does not provide an upper bound for the moving mass problem. The exploration of a series or sequence of moving masses led to the study of partially distributed moving masses traveling across a beam [7,8].

It has been shown that for masses moving across thin beams, the Euler–Bernoulli model is sufficient [9]. Work done by Rao demonstrated that the inertial effect of the mass is more important when it is traveling at lower velocities [10]. When including the inertial effects of a moving mass it was suggested by Lee [11] that if the contact between the mass and beam is to be modeled, then the separation of a mass at high velocities must be considered. When including a moving mass term the acceleration of the mass may be transformed from its total derivative form into partial derivative form that includes the local acceleration, the same as the beam, and the remaining "convective" terms [5,8]. The importance of the convective acceleration terms that arise when including a mass was analyzed [12] and it was found that when the mass is traveling at low velocities, these additional convective terms are negligible. Thus, a mass traveling across a thin beam may be modeled using a Euler–Bernoulli beam that includes inertial effects but ignores the contact forces and the convective acceleration of the mass [9–12].

A comprehensive finite element analysis was conducted by Lin and Trethewey [13] to model the response of a beam to moving force and moving mass, and additional attention was given to model the response due to a partially distributed moving mass [14]. More recently, an expansive tutorial on moving-load dynamic problems was conducted by Ouyang [15] that provides brief reviews of various types of moving load problems.

Once measurements or recordings of a structure's response have been taken and assuming no information about the excitation or structural properties is known a priori, OMA techniques such as EFDD, SSID and least squares frequency domain analysis may be used in order to discover the extent of modal damping. The EFDD method is an extension of the original Frequency Domain Decomposition (FDD) method developed by Brincker et al. [16]. The basis of this method is creating the spectral density matrix of the response and then performing singular value decomposition (SVD). From the singular values and singular vectors the modal frequencies and mode shapes may be recovered, and Brincker later demonstrated how the EFDD method could also produce the modal damping estimates [17]. The SSID method has applications in both the frequency and time domain, and many different variants of this method have been shown to be effective in estimating modal parameters [18]. The Enhanced Canonical Correlation Analysis (ECCA) proposed by Hong et al. in [19] is a time domain-based SSID method that uses weighting matrices to more effectively distinguish the structural modes from noise/numerical modes. It was shown in [19] that this method was developed with the aim of enhancing the estimation of modal parameters, such as frequency and damping, in long-span bridges. Among the more classical OMA methods, there are several frequency domain analysis methods that attempt to use different least squares based curve-fitting techniques to generate frequency response functions (FRF), and then modal frequency and damping can be estimated from the FRF [20].

Traditionally, an OMA approach requires assumptions of system time-invariance and ambient excitation, and thus it would be expected for there to be some difficulties encountered for the case of traffic loading. Specifically, the assumption of broad-banded excitation does not seem appropriate given the fact that vehicular traffic often has certain frequencies in greater proportion, but there have been developments in OMA that are aimed at dealing with excitation with frequency dominated components. With respect to FDD, Brincker et al. in [21] have presented methods of detection for harmonic components. Built into the ECCA method is a means of differentiating between true structural modes and spurious modes possibly arising from the frequency of the excitation using model order and singular values [19]. While using output only methods with structures excited by non-ambient white noise remains a challenge, the current state-of-the-art in OMA methods is designed to try to account for these issues.

In this paper, the response of a simply supported beam to a uniform partially distributed moving mass and several moving point loads was modeled using finite elements. The acceleration response of the beam was recorded at several discrete locations along the beam and these time histories were treated as the measurement channels. The EFDD, ECCA, and other curve-fitting techniques were investigated in order to determine their accuracy in providing modal damping ratio estimates. The main focus for the damping estimation was placed on the EFDD method since given its wide use, ready availability, and its incorporation into commercial codes.

2. Model formulation

2.1. Bridge model

The phenomena of traffic crossing a bridge, as represented by train and car crossings, were modeled using finite elements in MATLAB with the analogy of loads traveling across a beam. The beam model consisted of a large, continuous

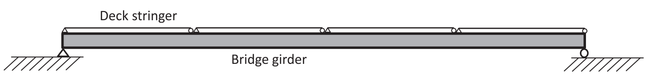

Fig. 1. Sample model set-up (actual model used later in simulations has 100 stringers).