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TIME-FREQUENCY-BASED ANALYSIS OF PEDESTRIAN INDUCED VIBRATION USING A TWO-STEP CLUSTERING APPROACH

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Summary

Vibration of footbridges caused by walking pedestrians is still an important research topic. The excitation is very complex and recent load models have shown to be sometimes un-conservative. Furthermore, cable-supported footbridges and stress ribbon footbridges have closely spaced natural frequencies. Well-known methods for modal identification such as frequency domain decomposition, subspace identification and blind source separation require comparatively long time series to work well. They sometimes have problems with transient frequency components of pedestrian induced vibrations. This paper presents a novel method to analyze the vibration of highly flexible footbridges. This method addresses three aspects: analyzing measurement data to understand the mechanics of the excitation, comparing the quality of load models with real excitation in the time-frequency domain and identifying modal parameters such as natural frequencies and mode shapes. This method utilizes a time-frequency analysis and a two-step clustering approach of the results. The implementation and advantages of this method are discussed using vibration data from an aluminum bridge at the University of Waterloo and a stress ribbon bridge at the TU Berlin. Furthermore, some interesting findings for pedestrian induced vibrations of both bridges are presented.

Keywords: human-induced vibrations; footbridge dynamics; time-frequency analysis; clustering; DBSCAN; operational modal identification; load model

1. Introduction

The novel method is based on the assumption that the response vector $x(t)$ of measurement is a linear combination of mixing vectors a_q also called shape functions and sources $s_q(t)$ according to Eq. 1. The response vector $x(t)$ are acceleration measurements with several sensors. The general term mixing vector is chosen because it is not calculated by solving an eigenvalue problem, or using a Singular Value Decomposition (SVD).

$$x(t) = A \cdot s(t) = \sum_{q=1}^Q a_q \cdot s_q(t) \quad (1)$$

2. Methodology

With time-frequency analysis, it is possible to identify and visualize especially non-stationary frequency content in three-dimensional time-frequency maps, because short time windows of the entire measurements are analyzed. The proposed method applies a time frequency analysis such as the continuous wavelet transform CWT directly to the signal of each sensor followed by a ridge detection algorithm. Instead of applying a SVD, the current mixing vectors are determined for all ridge points with the ratio of the time-frequency coefficients for each sensor. The clustering is performed in two-steps. The first step uses the

shape of the mixing vector and the second step frequency components of the sources as similarity measures. This enables the detection of different mixing vectors, which could occur at nearly the same frequency. This proved very relevant in the context of cable supported footbridges because of the closely spaced natural frequencies. The novel method includes the following steps:

- Step 1: Time Frequency Representation (TFR) based on a time frequency analysis and the Average Power Spectrum (APS)
- Step 2: Ridge Detection in the Average Power Spectrum (APS) – search for local maxima
- Step 3: Calculation of mixing vectors
- Step 4: Clustering of identified ridge points with the DBSCAN algorithm
- Step 5: Calculation of average frequencies, mixing vectors and relative energy of frequency components

3. Experimental studies

Vibration measurements have been conducted on an aluminum bridge at the University of Waterloo and the CFRP-stress ribbon bridge at the lab of TU Berlin, the latter with one person crossing the bridge with 105 BPM (1.75 Hz). A CWT is used for the TFR. The results of the novel method are presented in Fig. 1.

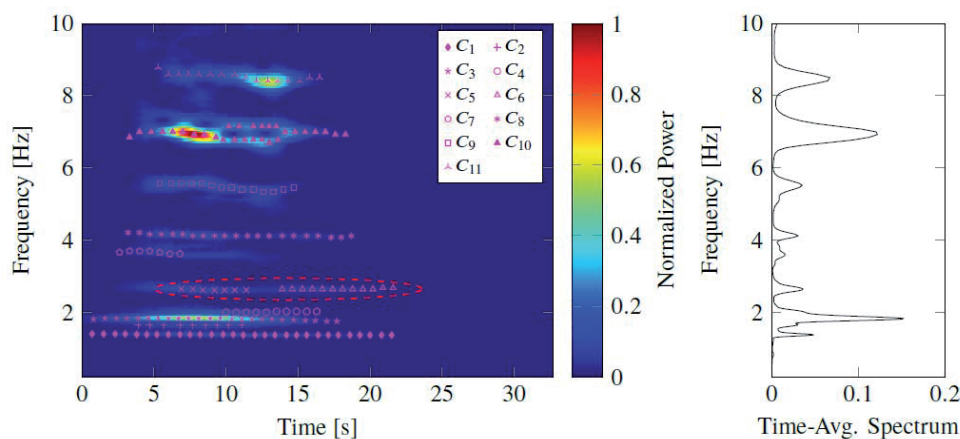


Fig. 1. APS of a vibration test on a stress ribbon bridge with a walking person (1.75 Hz / 105 BPM) and identified Clusters C_n . Dashed red line indicates ridge with changing mixing vector at constant frequency.

4. Discussion and Conclusions

A novel method based on time frequency analysis and clustering algorithms for analyzing vibration measurement data was presented. These clustering algorithms are applied in two steps. The first clustering step differentiates vibration components with different mixing vectors but with the same frequency. The second clustering step considering frequency similarity enables the distinction of structural modes with mode shapes that coincide due to a certain sensor layout. This method has been shown to be an excellent tool for analyzing the measurement data to understand characteristic of the excitation, for comparing the quality of load models with real excitation in the time-frequency domain and for identifying modal properties of structures such as natural frequencies and mode shapes. This novel method was applied to an aluminum truss bridge and a CFRP-stress ribbon bridge excited by a pedestrian. Natural frequencies as well as harmonics and subharmonics of the excitation frequency have been identified. The accompanying shape of the mixing vectors coincide very well with the mode shapes of these footbridges of a finite element analysis. Even for the excitation the shape of the mixing vector were identified. It was found that higher structural modes and higher harmonics of the step frequency can concentrate a significant amount of vibrational energy, which can potentially have implications in guidelines and codes.