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Time-dependent estimators for on-line monitoring of full-scale structures under ambient excitation

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ABSTRACT

The study described in this paper revisits the concept of instantaneous identification of system parameters based on time–frequency representations. In order to overcome the distortion caused by the time–frequency analysis window, optimal bias-compensated estimators are introduced. In particular, bias-compensated estimators are conceived specifically to provide on-line estimates for time-varying linear parameters such as instantaneous frequency and damping. With respect to previous studies, which relied on the concept of optimal time–frequency representation, the novel procedure corrects on-line estimates provided by standard representations. Afterwards, a practical application to a full-scale structure is presented. The church of "Madonnina della Neve" in Savigliano (Cuneo province, Italy) is a masonry building that exhibits defects in the connections between structural parts and visible cracks in lateral masonry walls. As a consequence, the global behaviour observed on this structure demonstrates significant flexibility in both the longitudinal and transversal directions. Recently cracks have worsened due to vibrations induced by traffic and heavy vehicles. Proposed bias-compensated estimators were used to analyse the unusual time-varying behaviour of the masonry structure, as observed from the response measured during the transit of vehicles and trucks.

1. Introduction

Vibration-based monitoring is one way to detect and quantify a degradation or damage in a full-scale structure [1,2]. On-line monitoring systems require standard operating procedures to provide estimates of quantities that may exhibit a time-varying behaviour after the fault occurrence (e.g. instantaneous frequency, stiffness or strength, damping and dissipation properties, etc.). In this context, classical time domain methods require to be adapted so as to provide on-line estimates of modal parameters [3,4]. Feldman proposed one of the first approaches to instantaneous parameter identification. He showed how to use the traditional definition of the analytic signal and the time-domain Hilbert transform in order to identify nonlinear models of S-DoF systems. In detail, the FREEVIB technique [5] is based on free vibration whereas the FORCEVIB [6] deals with forced vibration. These approaches can be used to construct the instantaneous

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damping and stiffness curves for a large class of systems, but are only suitable for single component signals [7]. A method for the decomposition of signals with multiple components into a collection of mono-components signals was proposed in [8] and it is now referred to as Hilbert–Huang transform in the time–frequency literature. The method has seen several applications in structural dynamics including linear system identification and damage detection, e.g. [9]. In the past, linear time–frequency representations have been often used in system identification. An overview of the use of wavelets in dynamics can be found in [10], whilst examples are reported by [11,12]. Quadratic representations have also received some attention [13,14,15].

The main problem with time–frequency representations is that they are intrinsically unable to identify an energy density at every point in the time–frequency plane, since the uncertainty principle does not allow such a notion. As a consequence, the definition of an instantaneous spectrum poses some conceptual problems [16,17,18], and the same difficulties apply to instantaneous estimates that are calculated from such representations. In the past a few techniques were proposed to select the optimal time–frequency representation, often based on optimisation procedures [19]. However, these methods are usually conceived to deal with stochastic processes and require a proper number of realisations. In the special case of linear time–frequency transforms, the uncertainty principle results in bias inevitably affecting the spectral function [20]. Consequently, parameters extracted from these representations (e.g. instantaneous frequencies, amplitudes and damping) will be biased as well, and corrections will be required.

The present study retrieves the concept of time-dependent or instantaneous identification with time–frequency representations, as already introduced in [1], to overcome the distortion effect caused by the time–frequency analysis window in the estimation of time-varying parameters such as natural frequency and damping. With respect to previous studies, which were mainly based on the concepts of optimal representation and optimal window, the newly proposed identification procedure applies corrections to on-line estimates provided by standard time–frequency representations. With the new method, corrections can be determined numerically, for different types of transforms and analysis windows, if a priori variation ranges of all the modal parameters are known in order to set the inputs of Monte Carlo simulations. In this study, a comprehensive set of Monte Carlo simulations was conducted for spectrogram time–frequency representations and correction polynomials were obtained so as to compensate for bias in damping estimates. Finally, an application to a full-scale structure will be presented. The little votive church of “Madonnina della Neve” in Savigliano (Cuneo province, Italy) is a masonry structure that presents a poor connection among structural parts and visible cracks in the lateral masonry walls. As a consequence, the global behaviour observed in this structure exhibits an unexpected level of flexibility in both the longitudinal and transversal directions. Recently cracking has worsened due to vibrations caused by traffic and heavy vehicles. The proposed bias-compensated estimators were used to study the non-stationary response of the masonry structure measured during the transit of vehicles and trucks.

2. Spectral representation of non-stationary stochastic processes and time–frequency estimators

The notion of spectral density, which is well consolidated in the field of stationary processes, constitutes a valuable starting point for approaching non-stationary processes. One of the reasons of the popularity of the Wigner transform is its desirable property to preserve the instantaneous spectral information in stationary processes. In fact, the Wigner spectrum of a stationary process F is independent of t and reduces to the spectral density of the process $S_F(f)$ [21,20]. An alternative idea to the Wigner transform is the spectrogram (SPEC), which, being based on running windows, can efficiently support an on-line implementation at a low computational cost, unlike a correlative transform structure. The SPEC, i.e. the square modulus of a short-time Fourier transform (STFT), of a stationary process may be written in the following form [20]:

$$E\left\{\mathrm{SPEC}_F^{(\gamma)}(t,f)\right\} = \int_{-\infty}^{\infty} \left|\Gamma(f'-f)\right|^2 S_F(f')\,df' \tag{1}$$

Where $\Gamma(f)$is the spectrum of a running window function $\gamma(t)$, such that $\|\gamma(t)\|=1$, and $S_F(f)$ is the spectral density associated with the process. Eq. (1) shows that the value of the spectrum at f is a weighted average of the spectral density, when $f\sim f'$. As long as the Fourier transform of the window is still localised near the origin, the SPEC provides, for each fixed f, information on the components of the original signal that in frequency domain are localised near f. Owing to the weighting average operation in Eq. (1), the SPEC or STFT spectral function is a biased estimator. An attractive idea is to extend the structure of Eq. (1) to locally stationary processes, as it is obtained by defining a local spectral density for an assumed stationarity interval δ [22]. If a SPEC representation is chosen, δ is implicitly assumed to match the length of the STFT analysis window. A time–frequency identification algorithm can be formulated to find the model parameters that minimise the error $Q(\mathbf{p})$ between a given time–frequency model, $\widetilde{\mathbf{T}}_{\mathbf{X}}(t,f;\mathbf{p})$, and the time–frequency transform of the measured signal, $\mathbf{T}_{\mathbf{X}_m}(t,f)$. In principle, a time–frequency model can be identified from the following minimisation [23,24]:

$$\begin{aligned} Q(\mathbf{p}) &= \|\widetilde{\mathbf{T}}_{\mathbf{X}}(t,f;\mathbf{p}) - \mathbf{T}_{\mathbf{X}_m}(t,f)\| \\ \mathbf{p}_{id} &= \arg\left[\min_{\forall \mathbf{p}} Q(\mathbf{p})\right] \end{aligned} \tag{2}$$

where, $\mathbf{p}$ is the global vector of the parameters of the time–frequency model and vector $\mathbf{X}_m$ contains the measured system response (e.g. displacement, velocity or acceleration). The “error function” Q provides a measure of the distance between the instantaneous spectral energy of the measured response $\mathbf{X}_m$ and that of the system output $\mathbf{X}$ corresponding to a