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Synchrosqueezed wavelet transform for damping identification

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ABSTRACT

Synchrosqueezing is a procedure for improving the frequency localization of a continuous wavelet transform. This research focuses on using a synchrosqueezed wavelet transform (SWT) to determine the damping ratios of a vibrating system using a free-response signal. While synchrosqueezing is advantageous due to its localisation in the frequency, damping identification with the original SWT is not sufficiently accurate. Here, the synchrosqueezing was researched in detail, and it was found that an error in the frequency occurs as a result of the numerical calculation of the preliminary frequencies. If this error were to be compensated, a better damping identification would be expected. To minimize the frequency-shift error, three different strategies are investigated: the scale-dependent coefficient method, the shifted-coefficient method and the autocorrelated-frequency method. Furthermore, to improve the SWT, two synchrosqueezing criteria are introduced: the average SWT and the proportional SWT. Finally, the proposed modifications are tested against close modes and the noise in the signals. It was numerically and experimentally confirmed that the SWT with the proportional criterion offers better frequency localization and performs better than the continuous wavelet transform when tested against noisy signals.

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1. Introduction

Damping is a mechanism that is present in every real vibrating structure. It originates as a combination of external factors, the properties of a structure and from the material itself. Identifying the damping together with identifying the natural frequencies is a key element in the characterization of a system.

The continuous wavelet transform (CWT) has been used as a tool for damping identification and has proven to be very useful, even for noisy signals [1–4]. For the extraction of the modal parameters, the CWT has been continuously studied and improved, e.g., with the introduction of the Gabor wavelet [5], the studies of the edge-effect and time-frequency localization [6,7] and to response from different excitation [8]. To improve the damping identification, different methods related to the CWT have been proposed, e.g., [9]. The CWT is being used for the damping identification in various different applications, e.g., on bladed disks [10], the damping of bridges [11] and in ocean engineering [12].

In order to improve the wavelet transform, synchrosqueezing has recently been proposed [13,14]. Synchrosqueezing adds to an existing transform by examining the local oscillations with respect to time. Based on this, synchrosqueezing re-

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allocates each value of the original transform to a new frequency on the time-frequency plane. The resulting time-frequency representation is thus sharpened in the frequency domain.

The synchrosqueezed wavelet transform (SWT) aims to combine the advantages of the CWT with the sharpening provided by the synchrosqueezing; it has been applied to a variety of different problems, often in the field of medicine [13], but also in the field of seismology [15].

In the field of mechanical engineering, the SWT has been introduced for the fault diagnosis of gearboxes [16–18]. Recently, generalized synchrosqueezed transforms have been introduced for bearings defects detection and diagnosis [19,20]. A comparison between the wavelet transform and its synchrosqueezed version was made in [21], where according to the authors, more visually appealing pictures appear to be the only advantage of synchrosqueezing. The synchrosqueezed wavelet transform has also been used for damping identification [22], being applied to seismic signals, where it has been compared to the wavelet and Hilbert–Huang transforms. It was found that although the SWT produces sharper representations, when identifying damping, it is less stable than the CWT-based approach.

In Section 2, the theoretical background to the continuous wavelet transform and synchrosqueezing are presented, followed by a method for damping identification based on the logarithmic decay of the envelope. In Section 3, some sources of error in the identification of damping with synchrosqueezing are addressed. The next section explores the effects of synchrosqueezing on signals with closely spaced modes. Section 5 focuses on the use of the SWT for damping identification. For better results, two modifications are proposed. Section 6 offers numerical experiments as well as an application involving real data. The last section draws the conclusions.

2. Theoretical background

In order to perform a wavelet transform, a mother wavelet function $\psi(t)$ is needed. According to Mallat [23], such a function must have a zero mean value (Eq. (1)) and has to be normalized (Eq. (2)).

$$\int_{-\infty}^{+\infty} \psi(t)\mathrm{d}t = 0 \tag{1}$$

$$\| \psi(t)\|^2 = \int_{-\infty}^{+\infty} |\psi(t)|^2\mathrm{d}t = 1 \tag{2}$$

The wavelet function $\psi(t)$ has to be translated in time by u and scaled by $s > 0$ to obtain a family of wavelet functions $\psi_{u,s}(t)$:

$$\psi_{u,s}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-u}{s}\right). \tag{3}$$

The continuous wavelet transform of a function $x(t)$ can now be defined as:

$$Wx(u, s) = \int_{-\infty}^{+\infty} x(t)\ \psi_{u,s}^*(t)\mathrm{d}t, \tag{4}$$

where $\psi_{u,s}^*(t)$ denotes a complex conjugate of the wavelet $\psi_{u,s}(t)$. The scale s and the angular velocity $\omega(s)$ are related via the frequency modulation η as: $\omega(s) = \eta/s$.

In this paper, the Gabor wavelet will be used:

$$\psi_{Gabor}(t) = \frac{1}{(\sigma^2\ \pi)^{1/4}}\mathrm{e}^{-t^2/(2\sigma^2)}\ \mathrm{e}^{\mathrm{i}\,\eta\,t}. \tag{5}$$

The parameter σ denotes the width of the Gaussian window of the Gabor wavelet. If $\sigma = 1$ is chosen, the Gabor wavelet becomes identical to the Morlet wavelet. Choosing appropriate values for the parameters σ and η is critical to the transform; they have to be small enough to reduce the edge effect and the time spread, yet large enough to reduce the frequency spread.

Synchrosqueezing, as defined by Daubechies et al. [13], requires three steps. The first step is to calculate a CWT for the (discrete) time u and the (discrete) scale s according to Eq. (4). In the second step, a preliminary frequency $\omega(u, s)$ is obtained from the oscillatory behaviour of $Wx(u, s)$ in u:

$$\omega(u, s) = -\mathrm{i}(Wx(u, s))^{-1}\frac{\partial}{\partial u}Wx(u, s). \tag{6}$$

In the third step the information is transformed from the time-scale plane to the time-frequency plane. Each value of $Wx(u, s)$ is re-assigned to (u, ω_l), where ω_l is the frequency that is the closest to the preliminary frequency of the original (discrete) point $\omega(u, s)$. This is formally written in Eq. (7):

$$T(u, \omega_l) = (\Delta\omega)^{-1} \sum_{s_k:|\omega(u,s_k)-\omega_l|\le\Delta\omega/2} Wx(u, s_k)s_k^{-3/2}\Delta s, \tag{7}$$

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