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Use of instantaneous estimators for the evaluation of structural damping

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Abstract

This study focuses on the definition of time–frequency instantaneous estimators to be employed in the identification of structural damping from signals measured in ambient vibration conditions. The estimators discussed here are obtained from instantaneous curve fitting applied directly to time–frequency representations of dynamic response signals. One of the strong points of this technique is its flexibility: from each signal, a time function of modal damping and amplitude is extracted, providing punctual information on the stability and consistency of damping estimate.

The aim of this paper is to study the implications related to the use of this method with linear time–frequency representations. Linear representations, within the inherent limits of their linear nature, still retain attractive computational advantages and lend themselves to a clear theoretical interpretation.

In the last part of the paper, a series of numerical applications to simple systems is presented to support theoretical argumentations. Finally, an experimental application to the identification of the damping in a real concrete building is shown.

1. Introduction

The field of structural identification now offers a vast range of effective techniques [1], which can operate in the time domain, the frequency domain or the joint time–frequency domain. In the sector of civil engineering, of special interest are "output only" methods, which do not require a prior knowledge of the dynamic input and are able to take advantage of the natural excitation to which a structure is subjected. Natural excitation is generally non-stationary, whilst an important characteristic seems to be the slow supply of energy, resulting in the response being interpreted as

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a sum of modulated harmonics concentrated at the modal frequencies. These considerations prompted some proposals for new identification methods designed to handle these types of non-stationary excitation [2–8].

Many stationarity-based techniques, such as autoregressive, random decrement based, subspace methods, etc. [1,9], are now also used in the presence of a low degree of stationarity, and can supply an acceptable level of accuracy in the estimate of modal shapes and frequencies. The situation is altogether different when an estimate of damping is required, since this parameter, having no experimentally significant effects on modal frequencies, primarily affects the modulation of modal signals and, in unknown input conditions, becomes latent information. In practice, the accuracy in damping estimation achieved with current "output only" techniques is not very high, and this is observed in particular when working with real structures. The problems encountered cannot be ascribed solely to noise, nor to non-linear effects, since even in the numerical applications errors of about 20% are seen to occur in stationary conditions (on less excited modes), whilst when the stationary condition is not respected, the errors can easily get as high as 100%.

This article focuses on the definition of an instantaneous estimator of damping for the identification of structures under unknown ambient excitation. Recently, some studies have proposed instantaneous curve fitting applied directly to time–frequency representations of dynamic response signals [6,10]. In the latter studies, instantaneous estimators were extracted from bi-linear-type time–frequency representations, due to their direct interpretation in terms of instantaneous energy, whilst this paper deals mainly with linear representations, which retain attractive computational advantages. In addition, linear representations lend themselves to a clearer theoretical interpretation, which may prove useful when dealing with difficult theoretical issues, such as selecting the best time–frequency representation.

A series of numerical applications to simple systems is presented to support theoretical statements and finally, an experimental application to the identification of instantaneous damping in a real concrete building is shown.

2. Time–frequency representation of stationary signals

One of the reasons of the popularity of the Wigner transform is its ability to preserve the instantaneous spectral information in stationary processes. In this case, in fact, the Wigner spectrum reduces to the usual spectral density [11]:

$$\mathrm{E}\{\mathrm{W}_f(t,\omega)\} = S_f(\omega). \tag{1}$$

Nevertheless, in the case of multi-component signals, the Wigner representation of a single realization is affected by spurious terms, which can be filtered out in the ambiguity function domain but at the cost of losing resolution. There is, in fact, a trade-off between cross term filtering and time–frequency resolution, and hence the representation is kernel dependent. Another problem is that the Wigner transform misses the desirable property of non-negativity over the *t–f* plane [8,12]. These two aspects may have some negative implications in the definition of instantaneous estimators to be used in the analysis of deterministic signals. Thus, while bi-linear representations are very useful in analyzing strongly non-stationary signals, choosing the best kernel to evaluate an instantaneous damping appears to be a challenging task, as relationships with dynamic response characteristics are far from trivial.

An alternative idea may be satisfaction with linear representations, which lend themselves to a clearer interpretation, and accepting the errors due to the fact that linear time–frequency transforms cause in general a distortion in the representation of the instantaneous power of stationary stochastic processes. Keeping in mind that any stationary signal may be obtained by H-filtering a white noise, the short-time Fourier transform (STFT), or Gabor transform, of a stationary process may be written in the form [11],

$$\mathrm{E}\{|\mathrm{STFT}_f(t,\omega)|^2\} = \frac{1}{2\pi}\int_{-\infty}^{\infty} |G(\omega'-\omega)|^2 |H(\omega')|^2 \, \mathrm{d}\omega', \tag{2}$$

where $G(\omega)$ is the spectrum of a window function $g(t)$, such as $\|G(\omega)\| = 1$. Eq. (2) shows that the value of the spectrum at $\boldsymbol{\omega}$ is a weighted average of the modulus of $H(\omega)$, when $\omega \sim \omega'$. As long as the Fourier transform of the window is still localized near the origin, the STFT provides, for each fixed ω, information on the part of the original signal which comes from the frequency contributions localized near ω.

As an example, by assuming the ergodicity of the signal, an estimator of the power spectrum, and hence of $|H(\omega)|$, may be defined in the following form:

$$V_B(\omega) = \frac{1}{B}\int_{-B/2}^{B/2} \left|\mathrm{STFT}_f(t,\omega)\right|^2 \mathrm{d}t. \tag{3}$$

Similarly, in the case of a time-scale (t–a) wavelet transform (WT) [11]:

$$\mathrm{E}\{|\mathrm{WT}_f(t,a)|^2\} = \frac{1}{2\pi}\frac{1}{a}\int_{-\infty}^{\infty} \left|\Psi(\omega')\right|^2 \left|H\left(\frac{\omega'}{a}\right)\right|^2 \mathrm{d}\omega', \tag{4}$$

where for the analyzing wavelet it is supposed that $\|\Psi\| = 1$. From Eq. (4), it is apparent that the weighed average interpretation is still valid.

For an example, and by assuming the ergodicity of the signal, the estimate of the spectral density may be written in following form:

$$\tilde{V}_B(a) = aV_B(a) = \frac{a}{B}\int_{-B/2}^{B/2} |\mathrm{WT}_f(t,a)|^2 \, \mathrm{d}t. \tag{5}$$

This estimator is called wavelet spectral function and supplies an estimate of the power spectrum, and hence of $|H(\omega)|$.

2.1. Locally stationary processes and instantaneous spectra

The concept of the locally stationary process has been developed in the classical works of Priestley [13]. In order to support an intuitive idea, suppose that for any t_0 the Wigner spectrum varies very little within an interval $[t_0-\delta, t_0+\delta]$. Such a parameter $\delta > 0$ is called the stationary length and in general its value depends on t_0. Consequently, a suitable choice for the window of a STFT should be a function compactly supported in the interval $[t_0-\delta, t_0+\delta]$ and may vary according to a proper temporal law, for example

$$\frac{1}{\beta(t)} e^{j\omega(t_0 - t)} g\left(\frac{t - t_0}{\beta(t)}\right), \tag{6}$$

where β is a scale factor changing over time according to the stationarity length of the process. The problem hence reduces to adapting the window (or the kernel, in the case of a Cohen class transform) to the process [14].

Several techniques have been formulated to select the best strategy and often they are based on optimization procedures. Recently, Kozek [15] proposed a minimum bias optimization criterion based on support properties of the ambiguity function. However, in principle, these methods are conceived to deal with stochastic processes or with a proper number of sample realizations and are not suitable to deal with a single signal.

Some new ideas may arise when working with random fluctuations produced by mechanical systems, which typically change slowly in time or space. These types of processes can be generally considered to be locally stationary, since they appear in the time–frequency plane as a sum of modulated harmonics concentrated at the modal frequencies. In this case, the instantaneous spectrum of a single realization may reflect and be associated with some physical parameters, whose consistency is an indirect indicator of the transform suitability.

An attractive idea is to extend by analogy some properties of stationarity to local stationarity. For instance, an instantaneous estimator for $|H(\omega)|$ may be defined by putting $B = \delta$ in Eqs. (3) and (5):

$$V(\omega, t) = \left|\mathrm{STFT}_f(t, \omega)\right|^2; \quad \tilde{V}(a, t) = a\left|\mathrm{WT}_f(t, a)\right|^2. \tag{7}$$

Actually, the latter statement is not as direct as may appear from the formal point of view and, since for Eq. (7) to constitute a physically meaningful estimator, some conditions have to be respected also on $|H(\omega)|$. This problem is one of non-stationary filtering and has been addressed by Priestley [13], Hammond and White [8] and, more recently, by Dalianis et al. [7], both referring to the concept of evolutionary spectrum.

3. Time–frequency instantaneous estimators

The following theories refer to linear structures subjected to unknown excitation and instrumented with simultaneous acquisition channels according to some of the n degrees of freedom. Usually, it is expected that under ambient excitation the release of dynamic energy from a system will be gradual enough to give rise to a response characterized by a number of modulated waveforms, so that in the time–frequency representation of the response signals, the energy appears to be concentrated around the modal frequencies and modulated according to the evolution of the time–frequency transform of the modulating waveform. Let $s_i(t)$ be the displacement at the ith position, $q_k(t)$ the displacement associated with the kth vibration mode, and finally, let u_{ik} be a term of the matrix of normalized eigenvectors, which decouples the motion equations; then we get [5]

$$s_i(t) = \sum_k u_{ik} q_k(t). \tag{8}$$

The individual modal component of the ith channel, which appears in the form of an energy peak in the time–frequency domain, can be written in its complex form as

$$s_{ik}(t) = u_{ik}q_k(t) = u_{ik}\tilde{q}_k(t)e^{j\omega_k t}, \tag{9}$$

where $\tilde{q}_k(t) = A_k(t)e^{j\varphi_k(t)}$ is a base-band signal, having introduced the following quantities, related to the kth mode: $A_k(t)$ and $\varphi_k(t)$, amplitude and phase modulating waveforms; ω_k, natural frequency. If the spectrum of $q_k(t)$ is single-sided, the complex form in Eq. (9) may be expressed through the analytic signal.

Due to the fact that in the (t, ω) plane the shape of the modulating waveform is maintained, the instantaneous amplitude ratio and phase difference between two measured signals $s_i(t)$ and $s_j(t)$ can be determined directly from their linear or bi-linear time–frequency auto and cross representations [5]: let $\mathrm{AR}(t, \omega)$ represent the time–frequency instantaneous estimator for the amplitude ratio, and $\mathrm{PH}(t, \omega)$ the time–frequency instantaneous estimator for the phase difference. Since they have been defined in the time–frequency plane, these estimators will retain some significance limits due to the uncertainty principle. On the other hand, in the time–frequency plane, close coupling occurs when components interfere in both time and frequency simultaneously, this being an advantage in comparison with classical frequency analysis.

In frequency intervals where a single modal component is predominant, the estimators tend to become steady in time. As this property increases progressively up to a peak at the modal frequencies, the latter can be identified by searching the minima of the estimators' standard deviation as a function of frequency. At a given identified modal frequency, the estimators supply amplitude and phase relationships between channels as a function of time, and, by averaging, an estimate of the modal shapes. Under these conditions, the identification of modal frequencies and shapes reduces to separating modal components and does not call for strict model assumptions, as in the method described only the stability over time of modal shapes has been imposed.

The present study focuses mainly on damping, and modal frequencies and shapes may be supposed to have been identified in a previous stage, even resorting to other techniques. The idea of assigning an instantaneous nature to damping is not questionable from a physical point of view, but it produces many counterintuitive consequences. In fact, the instantaneous response spectrum is conditioned by the signal's behaviour near time t, though, from a strictly energetic point of view, a change in the damping factor would affect only the following part of the signal. On the other hand, if the input is unknown, the local information about energy is missing. It can be concluded that the instantaneous damping defined here is only indirectly related to the physical concept of dissipation, but rather it reflects some local modulation characteristics of the response signal.

Based on the estimator defined in Eq. (7), some instantaneous parameters associated with the frequency response function (FRF), $H(\omega)$, can be estimated by minimizing the following functional at each time t [6]:

$$D(\omega, t) - |H(\omega, t)|^2. \tag{10}$$

In this minimization, there is an explicit assumption that the instantaneous energy spectrum $D(t, \omega)$ approaches a scaled version of the squared modulus of the FRF. In the case of a linear and proportionally damped structure one may write

$$H(\omega) = \sum_k \frac{\mathrm{AR}_k}{(\omega_k^2 - \omega^2 + 2\mathrm{j}\zeta_k\omega\omega_k)} \tag{11}$$

and instantaneous parameters for optimization may be chosen among modal amplitudes, AR_k, damping ζ_k, or modal frequency, ω_k.

As an example, if the parameters to be optimized are damping, ζ, and resonance amplitude, AR, in a s.-d.o.f. system, instantaneous estimators $\zeta(t)$ and $\mathrm{AR}(t)$ may be obtained by minimising an objective function defined as follows:

$$f(\zeta, \mathrm{AR}, t) = \int [D(t,\omega) - |H(\omega)|^2]\,\mathrm{d}\omega. \tag{12}$$

When working with m.-d.o.f. systems, a more general form for H will lead to a higher number of modal parameters to be optimized and, consequently, instantaneous parameters will be vectors with as many components as the number of modes to be estimated. A similar relationship could be written for velocity or acceleration signals.

Though alternative homogeneous forms may be adopted for this optimization problem, one of the advantages of using Eq. (12) is that, if the specific transform satisfies the time marginal condition (as in the case of the Wigner transform or the Spectrogram), this forces the regularized instantaneous spectrum arising from the optimization process to satisfy the same condition:

$$|s(t)|^2 = \int_\omega D_s(\omega, t)\,\mathrm{d}\omega = \int_\omega |H(\omega)|^2_{\zeta=\zeta(t);\mathrm{AR}=\mathrm{AR}(t)}\,\mathrm{d}\omega. \tag{13}$$

Eq. (13) shows that the instantaneous energy is not altered. Conversely, the frequency marginal, i.e., the spectral energy, which retains great significance in stationary signals, has been sacrificed.

3.1. Some issues on instantaneous curve fitting and estimation accuracy

Estimation accuracy depends on the relative energetic importance of the modes. In other words, the instantaneous estimator is more accurate in the temporal segments where the mode to be identified is predominant and is not affected by the residuals of the other modes. The definition of an instantaneous damping makes it possible to work out temporal weighted averages or to select temporal segments to improve the estimation of weaker modes.

A possible solution can be the introduction of functions allowing for the relative energetic importance of the kth mode as a function of time. In this connection, a proposal consists of using the following function, $w_k(t)$, either in the computation of weighted averages, or, having selected a threshold value, in the selection of time intervals where the estimate is deemed reliable [6]:

$$w_k(t) = \frac{\mathrm{AR}(t,\omega_k)/(2\omega_k^2\bar{\zeta}_k)}{\left|\sum_l \mathrm{AR}(t,\omega_l)/(\omega_l^2 - \omega^2 + \mathrm{j}2\pi\bar{\zeta}_l\omega_l\omega_k)\right|}, \tag{14}$$

where k identifies the mode in which damping is estimated and the sum is extended to all the modal components contained in the signal. The damping parameters that appear in the second member of Eq. (14) should be construed as tentative values (e.g., as obtained by averaging the instantaneous estimator over the entire temporal support considered).

Another important issue concerns the optimization procedure which, in the form expressed by Eq. (12), may give rise to problems of low sensitivity in the less pronounced modes in the time–frequency representation. To give more weight to the weaker modes, it has been proposed to make use of cross transforms with synthetic signals, whose energy is deliberately concentrated on the weaker modal components [6]. However, this technique, which can be applied solely when bi-linear transforms are used, can cause distortions in the estimate whose magnitude is not always foreseeable. An alternative possibility, that can be adopted even in the case of linear transforms, consists of performing the optimization in several steps, starting from an estimate of the most energetic modes and estimating the subsequent modes by difference.

Finally, it has been observed that the instantaneous optimization of the modal frequency, even when this is known a priori or from a previous identification, generally results in an improvement in the estimate of the other parameters. In other words, it seems that in the analysis of dynamic systems, even in linear and stationary conditions, it is of interest to define a 'ridge', i.e., the estimate of frequency modulation in the time–frequency domain.

4. Choice of the best representation for damping estimation

Numerical studies have been performed in order to identify the influence of the type of representation on the estimate of instantaneous parameters, with special regard to damping. The investigation focused on the influence of the following factors:

1. type of window to be used in the transforms,
2. time length of the window,
3. damping level of the structure.

In addition to considering the influence of these parameters, the numerous parametric analyses performed have also taken into consideration other factors, such as sampling frequency, signal length, and modal frequency.

In the case of the STFT, the length of the window in samples has been seen to affect damping estimates to a large extent. For the sake of brevity, only some of the results obtained are described below.

An extensive set of dynamic response signals has been created numerically by exciting simple linear oscillators by means of white noise. System characteristics were

- natural frequency of the oscillator: 10, 12, 20 and 40 Hz,
- damping of between 1.5% and 6%, with 0.25% intervals,
- sampling frequencies: 25, 50, 100 and 250 Hz.

As we have seen in the previous paragraphs, time–frequency transforms are able to supply an estimate of the FRF, on the basis of an average of the representations associated with a certain number of stationary response signals. Eqs. (2) and (4) show that, in the case of linear transforms, the window may cause an error in the estimate and that the latter, when the number of realizations approaches infinity, decreases with increasing window temporal length. An example of the evolution of the error in the estimate with increasing number of averaged realizations is illustrated

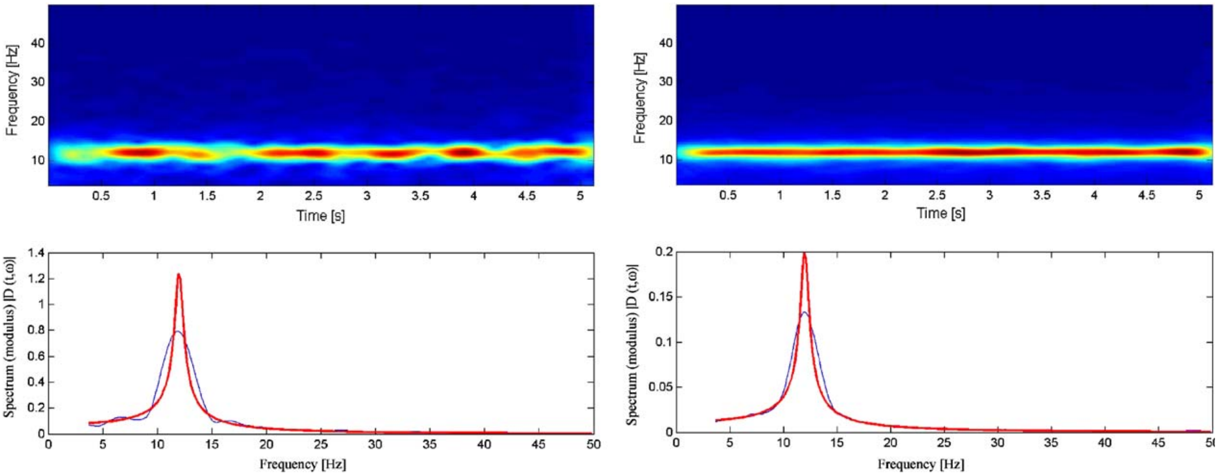

Fig. 1. STFT representations (Hanning window) obtained by averaging 5 and 30 realizations, respectively, and related FRF estimation. Legend: original instantaneous spectrum (thin line) and estimated spectrum (thick line).

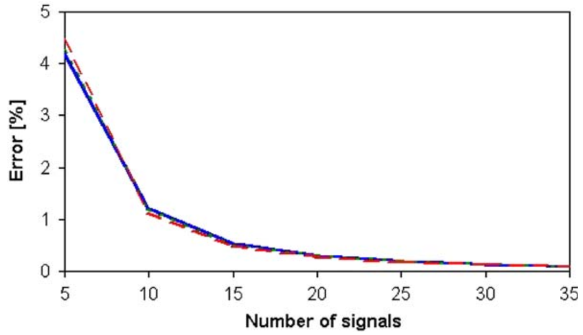

Fig. 2. Error in the estimate of the theoretical FRF from STFT representations as a function of the number of averaged realizations: - - - -, rectangular window; ______, Hanning window; ……, Hamming window.

in Figs. 1 and 2. In addition to the window length (Fig. 3), the effect of type of analyzing window (Hamming, Hanning, Rectangular, Triangular, Gauss and Blackman), has also been examined.

Charts were then created to illustrate the accuracy of curve fitting as a function the length of the windows in samples. The result, shown in Fig. 4, indicate that, averaging over a finite number of realizations (in this case 30), windows of optimal length exist for the estimate of the FRF and hence for the estimation of damping through the use of linear time–frequency transforms. Such lengths are identified by minimum points in charts of the type shown in Fig. 4.

Curves similar to these, not given here for the sake of brevity, have been obtained for different types of damping, modal frequency, number of signals, length of signal and sampling frequencies. In stationary conditions, the parameter that may affect the quality of time–frequency representations is the decorrelation length, and hence damping. Fig. 5, which has been obtained from simulated examples, shows the evolution of the optimal length that the windows should have

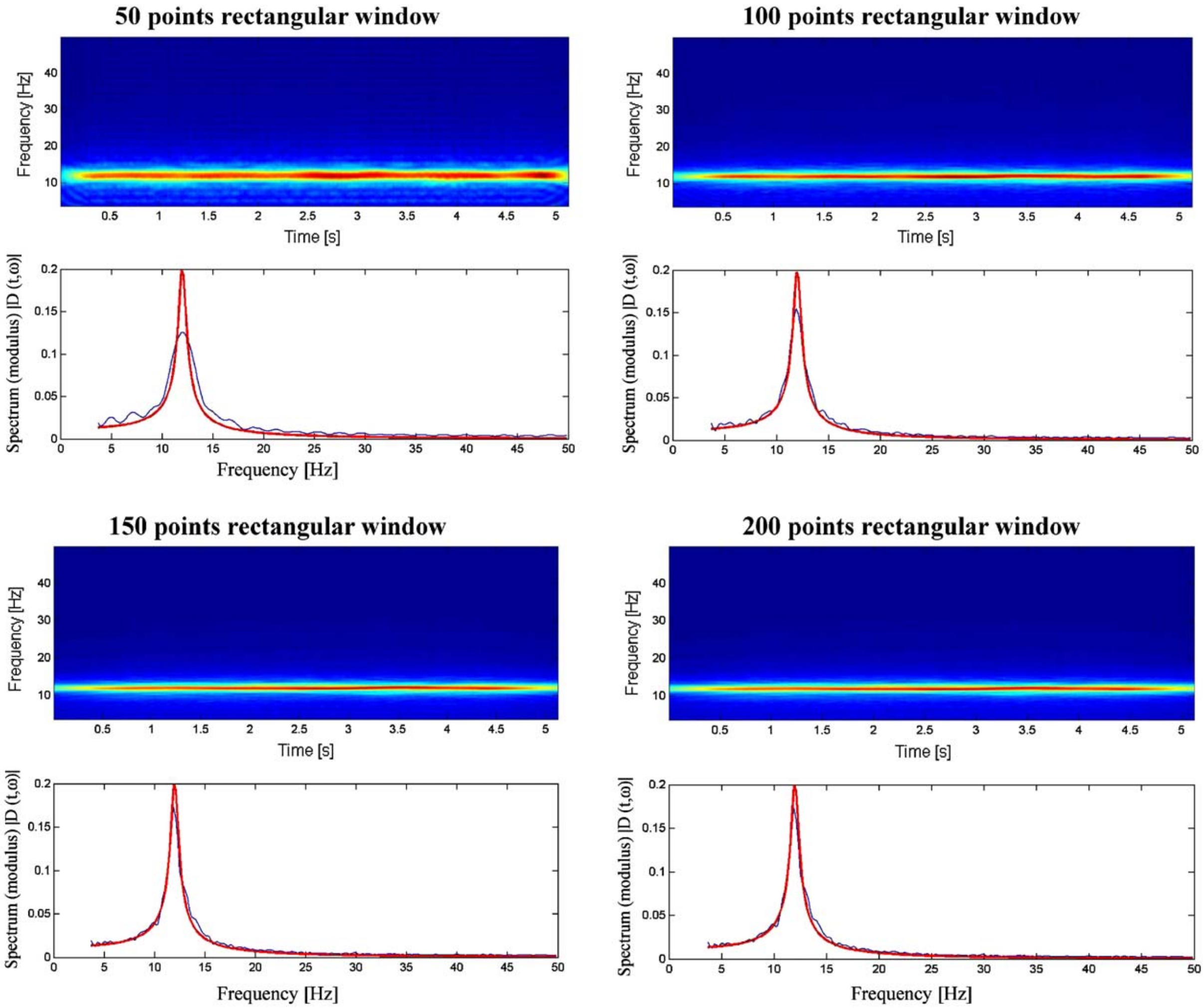

Fig. 3. FRF estimation from STFT representations (average over 30 realizations) as a function of the window length (rectangular window). Legend: original instantaneous spectrum (thin line) and estimated spectrum (thick line).

as a function of damping level (in this case for a Hanning-type window). Among other things, this chart has operational repercussions in terms of the selection of the time window in view of the applications.

In short, the choice of the optimal STFT representation for the estimate of the FRF, on the basis of a limited number of stationary realizations, seems to be governed primarily by the parameters analyzed above, namely: length in samples of the window, damping level, type of window.

Analyses of the same type were performed with Cauchy and Morlet type wavelets [10] and yielded the following conclusion: as the optimal length in samples of the analysis window depends also on modal frequency, the diversified effect of the wavelet on the different frequency

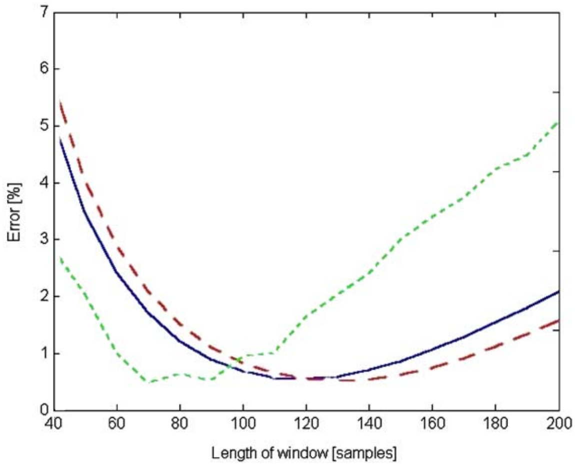

Fig. 4. Error in the curve fitting performed on STFTs as a function of window length (average over 30 realizations). ----, Hanning window; ____, Hamming window; ……, rectangular window.

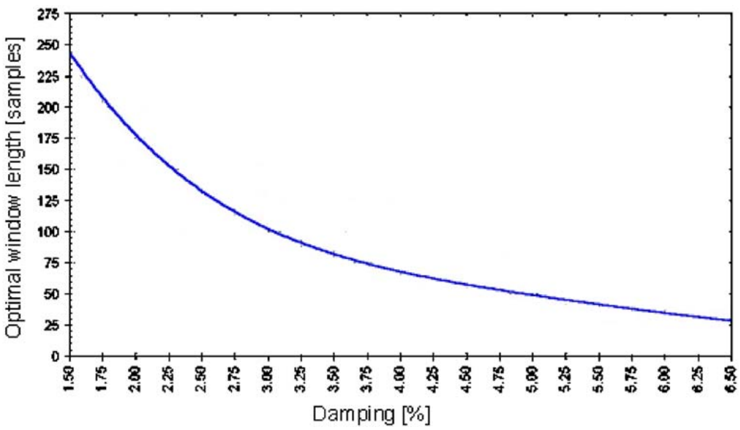

Fig. 5. Optimal length in samples of the STFT (Hanning window) as a function of damping level.

components makes the choice of an optimal window for m.d.o.f. systems less direct. These results, obtained on numerical models (shear-type frames), are a direct consequence of wavelet transforms' main characteristic, namely multi-resolution analysis, which makes the analysis of window length dependent on frequency. For this reason, in the application that follows, only STFTs are used.

5. Case study: application to the identification of a large R.C. building

This paragraph examines an application of time–frequency instantaneous estimators to the estimate of damping in a real concrete building: the Luciani Hospital of Caracas (Fig. 6).

Fig. 6. View of Luciani Hospital in Caracas [15].

The building consists of a central cross-shaped module and four square modules. In view of the geometry of the building, measurements were made on one of the four rectangular modules. These modules have nine structural storeys, the first four of which are rectangular, while the upper five have a central square hole.

The building was subjected to vibration measurements, within the framework of a pilot project sponsored by the Venezuelan Foundation for Seismological Investigations (FUNVISIS) [16]. The testing programme was conducted by means of Nanometrics sensors (Sensor Type: CMG40T) to obtain high-resolution measurements of vibration velocity in three directions. Three sensors were used simultaneously on line (15 min of recording, with 100 Hz sampling frequency); one of them was maintained throughout the testing programme in a barycentric position at foundation level, the other two were positioned at the third and top floors, first in a barycentric and then in an eccentric position, so as to be able to observe torsional modes. Tests were performed both under ambient excitation and in free decay conditions, brought about by the application of imposed initial displacements (actuator in an eccentric position at the top floor).

5.1. Structural identification

Based on signals acquired in ambient excitation conditions, structural identification was performed through a time-domain method (the Eigensystem Realization Algorithm (ERA) [17]) applied to random decrement functions and a time–frequency domain method (time–frequency instantaneous estimators (TFIEs) [4,5]).

Table 1
Structural identification of Domingo Luciani Hospital building from ambient excitation signals: modal frequencies and damping identified with ERA and TFIE methods

Mode	ERA		TFIE	
	Frequencies (Hz)	Damping (%)	Frequencies (Hz)	Damping (%)
1	2.37	2.51	2.35	2.76
2	2.70	2.18	2.68	2.97
3	3.25	3.79	3.30	3.21

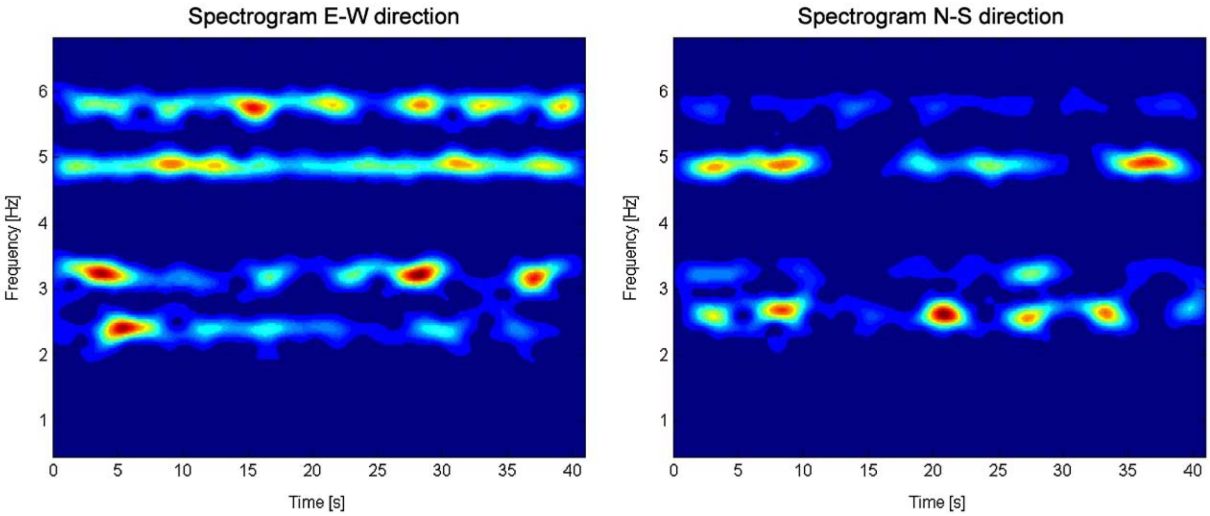

Fig. 7. Structural identification of a large r.c. building: spectrogram (square of the STFT) of two signals measured in E–W and N–S directions, respectively.

Table 1 lists the frequencies identified via the two methods mentioned above (ERA and TFIE). Modal shapes, omitted here for the sake of brevity, showed that these frequencies corresponded to the first three modal frequencies of the structure. The first (2.35–2.37 Hz) in the East–West direction, the second (2.68–2.70 Hz) in the North–South direction and the third (3.25–3.30 Hz) with marked torsional components.

In addition to the frequencies identified with certainty, and classified with the aid of their modal shapes, higher frequencies were also observed whose classification was not as evident and should have required a model that allowed for the stiffening effect of the infilled walls. This effect may be assessed through a process of model updating on the basis of the frequencies classified with certainty [4]. Fig. 7 shows the STFT representations of two signals measured along the two principal directions, which are able to represent the components associated to the main modes.

5.2. Identification of damping

As mentioned before, another type of dynamic test was performed by imposing an initial displacement of the structure with the aid of a hydraulic actuator positioned at roof level. This type of excitation made it possible to work out, by means of current techniques, a simple, reliable assessment of damping that served as a useful comparison with the results yielded by the methods employed in ambient excitation conditions. It is known, in fact, that the latter situation is more critical, as it generally requires more complex identification tools leading to less accurate results.

Results of damping identification, in ambient excitation and free decay conditions, respectively, are summarized in Tables 1 and 2. The identification procedure will be illustrated in detail for the third identified mode, involving a strong torsional component, which had turned out to be highly energetic in all measurements. The identification of viscous equivalent damping on the basis of free decay signals was conducted through a simple fitting procedure in the time domain (Fig. 8), with the prior use of a band-pass filter. Demodulation and fitting techniques in the frequency domain were also used, which yielded virtually identical damping values.

In greater detail, curve fitting consisted of calibrating three parameters: amplitude, frequency and damping. The results were substantially confirmed in all tests, and Table 2 shows the final

Table 2
Results of identification procedure in free decay conditions

Mode	Frequencies (Hz)	Damping (%)
1	2.35	2.71
2	2.68	2.78
3	3.21	3.15

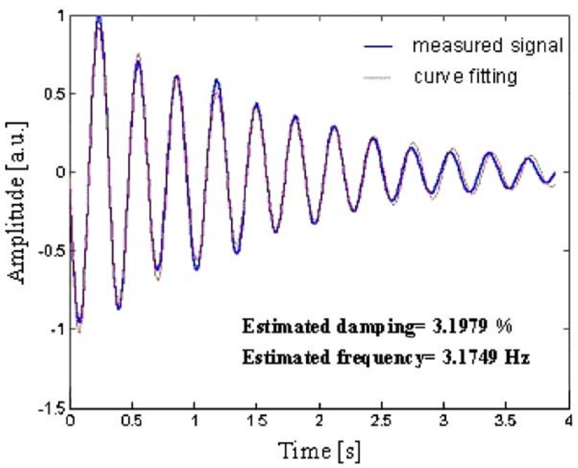

Fig. 8. Sample curve fitting (dark line) in time domain over a free decay signal (grey line). The parameters estimated from this signal for the third vibration mode were: damping, 3.1979%; frequency, 3.1749 Hz.

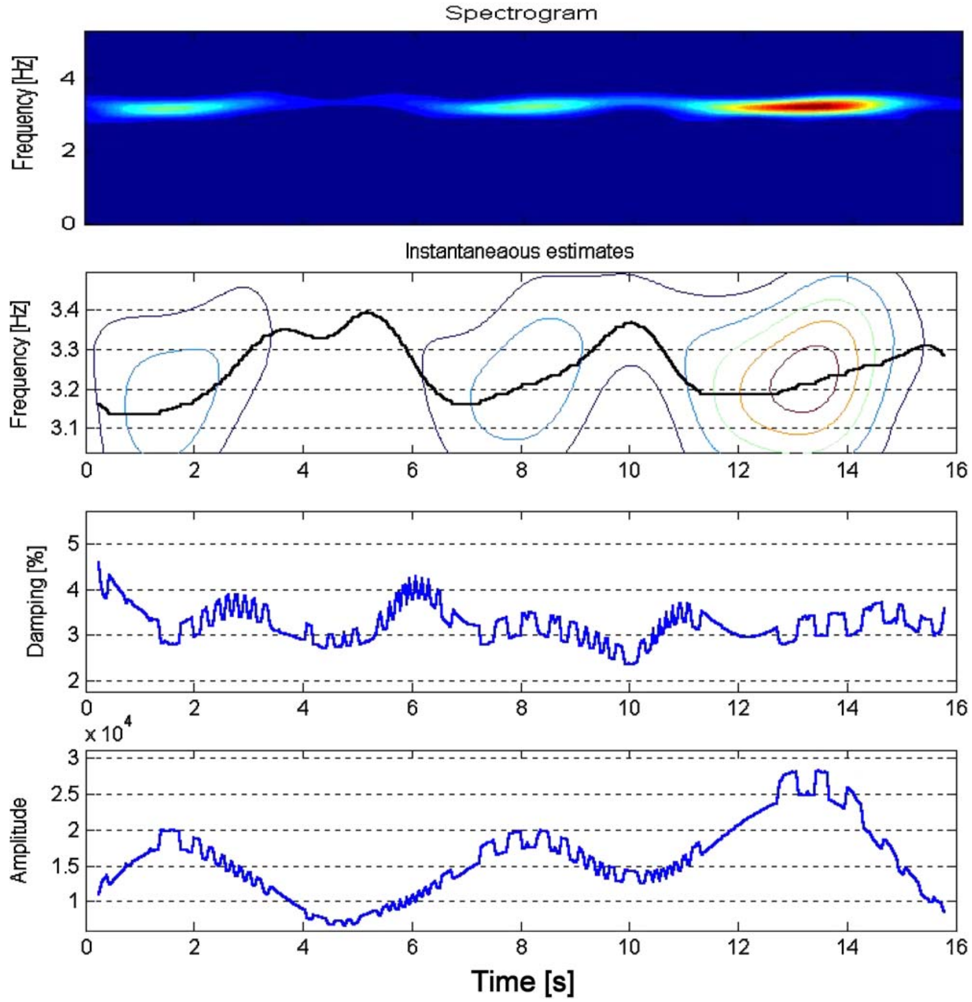

Fig. 9. Instantaneous estimators calculated for the third vibration mode on a signal measured under ambient excitation.

result of the identification procedure, worked out by averaging the values identified in the different tests.

Instantaneous damping estimators from measurements made in ambient conditions are now examined. With reference to Fig. 5 and in view of the damping level, the analyzing window selected for the STFT analysis was a Hanning-type window with length = 100 samples.

Fig. 9 shows the results obtained from the analysis of one of the signals relating to ambient excitation. From this figure, we can see that the estimates turned out to be excellent, especially in the time segments where the amplitude of the modal component to be identified was greater, in agreement with the considerations prompted by the previous numerical analyses. Modal frequency estimates also turned out to be good at these time segments.

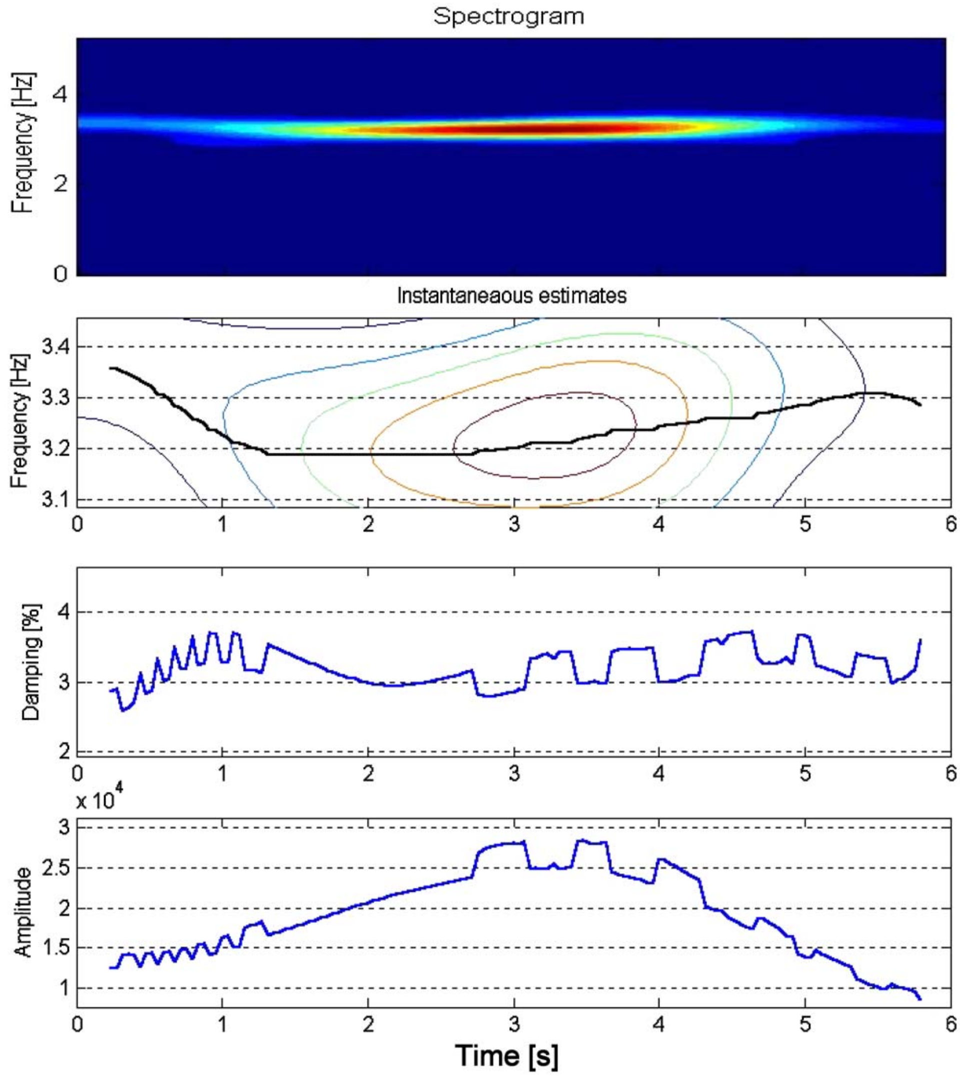

Fig. 10. Instantaneous estimators calculated for the third mode on a signal measured under ambient excitation: selection of a time segment characterized by pronounced amplitude.

Finally, another estimate was performed on the same signal, using the same analyzing window length (100 samples), but limited to the segment characterized by maximum amplitude, which is shown in Fig. 10 together with the instantaneous estimators calculated. In this case, the estimate of damping, obtained from a single signal with an average weighted according to Eq. (14), turned out to be 3.21% vs. 3.15% (damping calculated from free decay signals), with an estimate error smaller than 2%. Thus, in this application, the accuracy afforded by the damping estimation method based on time–frequency instantaneous estimators was seen to be appreciably higher than the accuracy offered by the ''output only'' methods currently employed to identify structures on the basis of their response to ambient excitation.

6. Conclusions

This report was devoted to the definition of an instantaneous damping estimator for use in the interpretation of dynamic tests performed on structures subjected to ambient excitation. The significance of this investigation is confirmed by the fact that many of the "output only" methods currently employed often display limitations precisely when it comes to providing an accurate and reliable assessment of structural damping.

The specific aim of this paper is to examine and define instantaneous estimators based on linear transforms, such as the short time frequency transform (STFT) which, despite their intrinsic limitations, offer appreciable computational advantages. Among other things, the simple structure of these transforms made it possible to address in a direct manner the difficult problem of the optimal time–frequency representation, also through a series of parametric analyses for the selection of the best type of analyzing window for identification purposes. In this connection, parametric investigations were performed on elementary dynamic systems.

The last part of the study illustrates the application of the identification methods to a large r.c. building. The identification of modal damping, which had already been determined with accuracy through a series of free decay tests performed by means of jacks, was performed by processing the signals produced in ambient excitation conditions. To this end, instantaneous estimators were constructed on the basis of STFT time–frequency representations, which yielded an accurate estimate of damping. It should be noted that the latter experience represents the first documented application of a time–frequency instantaneous estimator to the evaluation of damping in a large civil structure.

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