Aalborg Universitet

Damping Estimation Using Free Decays and Ambient Vibration Tests

Magalhães, Filipe; Brincker, Rune; Cunha, Álvaro

Published in:
Proceedings of the 2nd International Operational Modal Analysis Conference

Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Magalhães, F., Brincker, R., & Cunha, Á. (2007). Damping Estimation Using Free Decays and Ambient Vibration Tests. In R. Brincker, & N. Møller (Eds.), Proceedings of the 2nd International Operational Modal Analysis Conference (Vol. Vol. 2, pp. 513-521). Aalborg Universitet.

DAMPING ESTIMATION USING FREE DECAYS AND AMBIENT VIBRATION TESTS

Filipe Magalhães, Faculty of Engineering of the University of Porto, Portugal

Rune Brincker, Aalborg University, Denmark

Álvaro Cunha, Faculty of Engineering of the University of Porto, Portugal

filipema@fe.up.pt

Abstract

This paper aims the study of the accuracy provided by the identification of modal damping ratios based on ambient and free vibration tests. For that purpose, numerical simulations were developed to generate artificial experimental data concerning both types of tests. This simulated data allowed the illustration of the influence of factors like non-proportional damping or the proximity of natural frequencies on the quality of the estimates. The accuracy of two output-only identification algorithms (Enhanced Frequency Domain Decomposition and Covariance driven Stochastic Subspace Identification methods) and of two alternative procedures to process the free decays was also analyzed.

1 Introduction

The accurate identification of modal damping ratios of Civil Engineering structures is a subject of major importance, as the amplitude of structural vibrations in resonance is inversely proportional to these coefficients. Their experimental identification can be performed either from ambient vibration or from free vibration tests. In the last case, the structural response after application of an impulse or after the application of harmonic loads can be used. Ambient vibration tests have the strong advantage of being more practical and economical. However, recent applications of both approaches in Civil Engineering structures have shown some discrepancies [1, 2]. Thus, it is important to evaluate the accuracy of the available testing alternatives.

2 Experimental techniques for damping estimation

Civil Engineering structures are usually difficult to excite artificially, due to their size. Therefore, the most practical and economical approach for the identification of modal parameters is based on the use of the structural response to ambient loads. The first step in the experimental characterization of the dynamic behaviour of an existing structure should then consist in the performance of an ambient vibration test. This type of test allows the identification of natural frequencies, mode shapes and modal damping ratios, using just some accelerometers.

The quality of the estimates of natural frequencies and mode shapes provided by the current output-only modal identification techniques is not contested. However, the corresponding modal damping estimates show usually significantly higher dispersion. That is why it is still very common to perform complementary free vibration tests, when the accurate identification of modal damping ratios is required.

In this section, practical aspects and theoretical background of both approaches are briefly described.

2.1 Ambient Vibration Tests

During the ambient vibration tests, the accelerations of structures excited by ambient loads are measured. Accordingly, the traffic over the bridge and the wind are welcome, to increase the signal intensity of the measured time series. Because the levels of excitation are generally low, the used accelerometers have to be very sensitive. When the size of the structure is considerable, the use of wireless systems duly synchronized by GPS is advantageous (Figure 1 show the use of seismographs synchronized by GPS in the ambient vibration test of a bridge in Porto [3]).

Figure 1 – Ambient Vibration test of a bridge in Porto

The recorded data is then processed using output-only identification tools. Nowadays, there are several robust methods, working in time or in frequency domains, which are already implemented in user-friendly software [4, 5]. A review of the most commonly used methods in civil applications can be found in reference [6].

In the present work, only two methods are studied: the Enhanced Frequency Domain Method (EFDD) and the Covariance driven Stochastic Subspace Identification Method (SSI-COV). The first one is a non-parametric frequency domain method, whereas the second one is a parametric time domain method.

1.2.1 The Enhanced Frequency Domain Method

The first step of this method is to construct a spectral matrix of the ambient responses, with one row for each measurement point and one column for each point elected as reference. Therefore, the columns contain the cross spectra relating the structural response at all measurement points with the corresponding response at each reference point.

It can be shown [7] that, under some assumptions (white noise excitation, low damping and orthogonal mode shapes for close modes), the singular values of the spectral matrix are auto-spectral density functions of single degree of freedom systems with the same frequency and damping as the structure vibration modes.

Auto-correlations functions, associated with the different modes of the structure, can be calculated by applying an inverse FFT to the auto-spectral density functions. From these functions, it is straightforward to identify the modal damping ratios and obtain enhanced estimates of the natural frequencies. These frequencies are evaluated looking at the time intervals between each zero crossing. The modal damping ratios are estimated adjusting an exponential decay to the relative maxima of the auto-correlation functions. Mode shapes are identified from the singular vectors of the spectral matrices evaluated at the identified resonance frequencies and associated with the singular values that contain the peaks.

In this paper, this method is applied using the Artemis software [4].

2.2.1 The Covariance driven Stochastic Subspace Identification Method

The Covariance driven Stochastic Subspace Identification method (SSI-COV) performs the identification of the modal parameters using a stochastic state space model that, in its discrete form and assuming the excitation as a white noise, is represented by the following equations:

$$\begin{aligned} x_{k+1} &= A \cdot x_k + w_k \\ y_k &= C \cdot x_k + v_k \end{aligned} \qquad (1)$$

Identification of matrices *A* and *C* is performed from the correlation functions of the measured responses time series. The algorithm of the method is based on the properties of stochastic systems [8] and involves a singular value decomposition and the resolution of a least-squares equation.

After identification of the state space model, modal parameters are extracted from matrices *A* and *C* [9]. It is worth noting that, the identification of the state space model requires the definition of the order of the model. However, for real Civil Engineering Structures it is not possible to predict the order of the model that better fits the experimental data and more realistically characterizes the dynamic behaviour of the structure. The most appropriate way to overcome this difficulty is to estimate the modal parameters using models with an order within an interval previously defined in a conservative way. The identified modal parameters are then represented in a stabilization diagram. This diagram shows parameters that are stable for models of increasing orders, and these are the ones with structural significance. The others are just associated with numerical modes, which are important to model the noise that exists always in measured data.

In this paper this method is applied using MatLab routines developed at the University of Porto [10].

2.2 Free Vibration Tests

The free vibration tests performed in Civil Engineering structures for identification of modal damping ratios can be of two types: measurement of the free response after application of a sinusoidal load with an excitation frequency coincident with one of its natural frequencies and measurement of the free structural response after the application of an impulse (or imposed displacement).

The application of a resonant excitation can be done using several different ways. For instance, in a flexible footbridge, a jumping pedestrian can be enough, while in a flexible roof, a cable connected to a rotating engine can be used [1]. However, in a more massive structure, a heavy exciter has to be employed. The load must be applied at the anti-node of the mode that is being excited. Therefore, the performance of these tests depends on the prior prediction of the structure natural frequencies and mode shapes, which can be achieved developing previously an ambient vibration test.

The decays measured after application of the force should contain only the contribution of a single mode, the modal damping ratio being then directly estimated by fitting an exponential function to the relative maxima of the recorded decay.

The application of an impulsive load is usually performed by the sudden release of a mass previously suspended from the structure. In this type of tests, the prior identification of the mode shapes is also important, because the mass must be hanged in a point where the most important modes have significant modal components.

The most traditional procedure to analyse the recorded data consists in the application of band-pass filters to isolate the contributions of the most important modes. This filtered data is similar to the time series that are colleted after a sinusoidal excitation. Thus, from this point the followed procedure is the same that was described for the other type of excitation.

Figure 2 shows free decays measured in the suspended roof of a stadium after the application of a sinusoidal resonant load and after the application of an impulse.

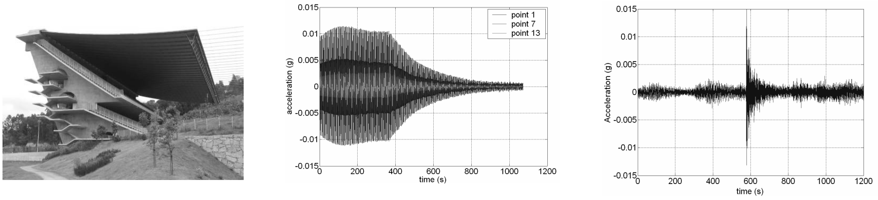


Figure 2 – View of Braga Stadium and records of measured decays in the roof after the application of a sinusoidal resonant load and after the application of an impulse [1].

3 Analysis of simulated data

3.1 Description of the simulated models

The simulation of dynamic tests involved models with two degrees of freedom. To test the accuracy of the techniques under evaluation, 6 different scenarios were considered. These are characterized in Table 1, which contains the theoretical values of natural frequencies and modal damping ratios and a measure of the non-proportionality of the damping matrices. The studied models differ on the proximity of the two natural frequencies (sm – well separated modes; cm – closely spaced modes) and on the type of damping (proportional or non-proportional). This last aspect has influence on the characteristics of the mode shapes, which are real if damping is proportional and can become complex if damping is not proportional. Damping is proportional if the damping matrix in the modal space is diagonal. Thus, damping non-proportionality can be quantified by the ratio between the sum of the absolute values of the off-diagonal elements and the sum of the absolute values of the diagonal elements of the modal coordinate damping matrix.

Table 1 – Characteristics of the simulated models (f – natural frequency; ξ – modal damping ratio)

Model	Characterization	Measure of damp. non-proportionality	Mode 1		Mode 2	
			f (Hz)	ξ (%)	f (Hz)	ξ (%)
sm1	No modal complexity	0.0	1.2995	1.0410	1.5915	2.0000
sm2	Some modal complexity	0.2	1.2996	1.0408	1.5915	2.0002
sm3	Strong modal complexity	1.0	1.3011	1.0353	1.5896	2.0061
cm1	No modal complexity	0.0	1.5720	1.0124	1.5915	2.0000
cm2	Some modal complexity	0.3	1.5727	0.9746	1.5909	2.0378
cm3	Strong modal complexity	1.0	1.5471	1.1218	1.5791	1.9246

The ambient vibration tests were replicated adopting as inputs for the models time series with normally distributed random numbers. The simulated free decays are the responses of the models to imposed initial conditions. For the generation of free decays after the application of a sinusoidal load in resonance, the imposed displacements have the modal ordinates of the excited mode; for the simulation of free decays after the application of an impulse, a displacement in a degree of freedom where both modes have significant modal ordinates is imposed. A sampling frequency of 5 Hz was adopted in all the simulations.

The responses were evaluated using a vector ARMA model to ensure that the simulated responses are covariance equivalent [11].

3.2 Ambient Vibration Tests Simulation

Firstly, the simulated responses of model sm1 excited with a random load (white noise) were used to study the influence of the adopted time length in the estimated modal damping ratios. In this analysis no noise was added to the responses. The artificially generated responses were processed by the EFDD and SSI-COV methods.

In the application of the EFDD method the number of performed averages was kept constant and equal to 40. So, for the different time lengths, different window lengths were adopted: 128, 256, 512, 1024 and 2048 points.

In the application of the SSI-COV method, the number of block columns of the Toeplitz matrix was the same for all the time lengths and was equal to 20. The modal parameters were extracted from models of orders around 10.

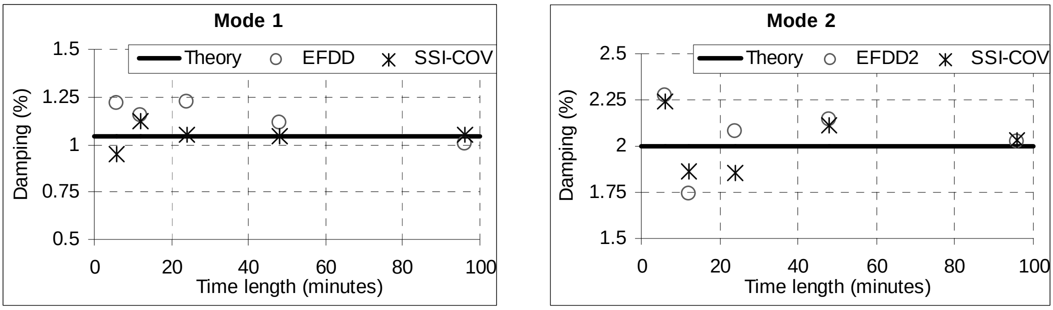


Figure 3 – Variation of the estimated modal damping ratios with the length of the used time segments.

The results presented in Figure 3 show that the quality of the estimates increases with the increase of the time series length. This effect is more pronounced in the results of the EFDD method for the first mode (the error decreases from 25% to 3%).

Then, both identification methods were applied to ambient responses simulated for the six models described in Table 1. In these analyses time segments with 50 000 points were used (10 000 seconds) and the effect of noise was considered. The noise was simulated by time series of random numbers normally distributed and a noise to signal ratio of 10% was adopted (value defined taking it account the values observed in a bridge test where the observed noise percentage was relatively high [2])

The graphics of Figure 4 show the obtained results. The errors tend to increase with the increasing modal complexity and with the proximity of the natural frequencies. However, all the errors are lower than 22 %. These results are important to illustrate that the applied output-only techniques provided good estimates even in the extreme case of high modal complexity associated with closely spaced modes. It is also important to note that in the critical models (sm3 and cm3), the errors associated with the two applied techniques present significant differences. This shows the importance of applying always at least two different techniques in order to have an idea of the quality of the results.

The use of long time series allowed the development of many averages, which minimized the effect of the added noise.

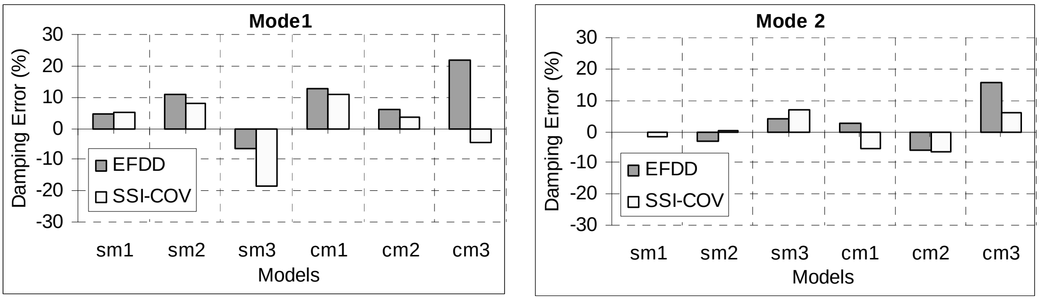


Figure 4 – Errors of the modal damping ratios estimates provided the EFDD and SSI-COV methods for the six studied models.

3.3 *Free Vibration Tests Simulation*

In the simulation of the free vibration tests, noise was added to all the simulated responses. But, in this type of tests the noise to signal ratio is very small when compared to the observed in ambient vibration tests, because the level of vibration is much higher. So, it was adopted a ratio of 0.1%, using data measured during a bridge test [2] as reference (the accelerations measured during the free decays were approximately 100 times higher than the responses measured during the ambient vibration test).

In this work, the two types of free vibration tests usually performed in Civil Engineering structures were studied. Initially, the free decays observed after the application of a sinusoidal load in resonance were analysed. Then, the quality of the estimates extracted from free decays measured after application of an impulse was evaluated.

In the first type of test, the traditional analysis, described in section 2.2 (fitting of an exponential decay), assumes that the decay has only the contribution of a single mode. It is well know that this assumption is close to reality when damping is small and proportional and the modes are well separated. The first graphic of Figure 5 presents the decays simulated for the first mode of model sm1, to show that for this model the referred assumption is valid, as the estimated modal damping ratio (1.037%) is very close to the theoretical value. The second graphic of Figure 5 shows similar simulation for the second mode of model cm3. In this case, it was not possible to get a decay with just the contribution of the second mode, because there is a strong coupling of the two modes of the model. In the beginning of the decay, the second mode is dominant, but at the end, the first one becomes dominant, as it has lower damping. Therefore, the modal damping ratio provided by the exponential fitting gives a wrong estimate for the damping of the second mode.

Table 2 resumes the results provided by the exponential fitting applied to the simulations of the free decay, when trying to have just one dominant mode. The presented results show that this traditional procedure produced reasonable results, except for the model with high modal complexity and closely spaced modes.

As alternative to this rather simple procedure, the output-only SSI-COV method can be used to extract the modal parameters from measured free decays. The free decays observed after the application of impulses or imposed displacements are proportional to the correlations of the responses associated with a white noise excitation. Consequently, these measured free decays can be used as input of the SSI-COV method, taking the place of the correlation functions calculated from the ambient responses. This approach overcomes the limitations of the traditional procedure, due to the fact that, in this method, a model with non-proportional damping is fitted to the data.

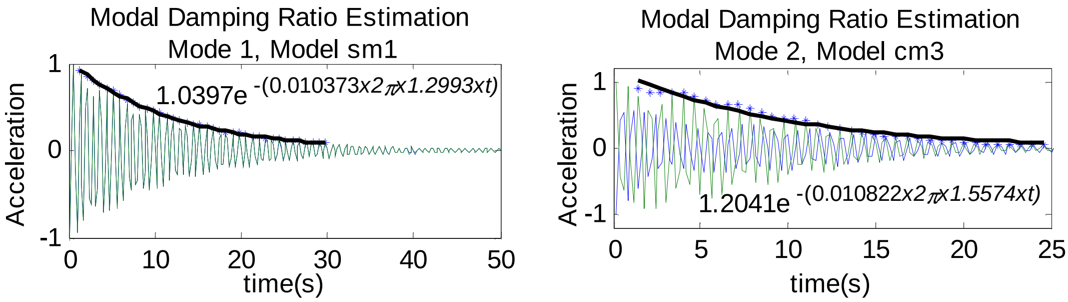


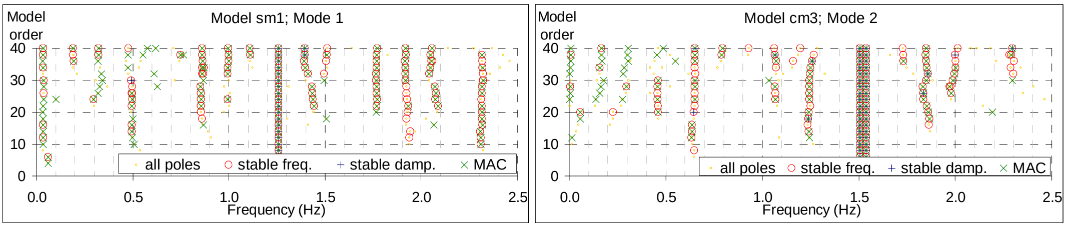
Figure 5 – Simulated free vibrations after application of imposed displacements equal to the modal ordinates of one of the modes and estimation of the modal damping ratios.

Table 2 – Modal damping ratios estimated from free decays using the exponential fitting

Model	ξ (%) Mode 1	ξ (%) Mode 2
sm1	1.037	2.017
sm2	1.038	2.028
sm3	1.037	2.075

Model	ξ (%) Mode 1	ξ (%) Mode 2
cm1	1.022	2.017
cm2	1.067	2.308
cm3	1.022	1.082

Figure 6 shows the modal damping estimates and the stabilization diagrams that come from the application of the SSI-COV method to two of the simulated free decays: a) decay of model sm1 with dominant contribution of mode 1, b) decay of model cm3 with dominant contribution of mode 2. It is interesting to observe that, this methodology enabled the estimation of modal damping ratios that are almost coincident with the theoretical values, even for the worst situation with closely spaced modes with high modal complexity.



ξ mode 1 – 1.041 %

ξ mode 1 – 1.122 % ; ξ mode 2 – 1.925 %

Figure 6 – Stabilization diagrams of the application of SSI-COV algorithm to the free decays.

This methodology can also be applied to free decays measured after the application of impulses. In this case, with just one impulse, it is possible to identify all the modes that have significant modal ordinates at the degree of freedom where the impulse was applied.

The analysis of the simulated free decay after the application of an impulse to the six studied models showed very good estimates. These results, provided by the analysis of the six stabilization diagrams, are presented in Table 3.

Table 3 – Modal damping ratios estimated by the SSI-COV method from the free decays associated with the application of an impulse.

Model	ξ (%) Mode 1	ξ (%) Mode 2
sm1	1.041	2.000
sm2	1.040	2.000
sm3	1.036	2.006

Model	ξ (%) Mode 1	ξ (%) Mode 2
cm1	1.012	2.001
cm2	0.975	2.038
cm3	1.122	1.925

This technique has been already applied with success to the data colleted after the application of an impulsive load in a Portuguese cable-stayed bridge [12].

4 Conclusions and future research

The analysis of the simulated data showed that the ambient vibration tests together with the application of state-of-the-art output-only identification techniques can provide good estimates (errors lower than 22%) of the modal damping ratios of structures with closely spaced modes and non-proportional damping. Nevertheless, the achievement of good results is dependent on the length of the collected time series. Therefore, long time segments should be used. For Civil Structures with a first natural frequency of about 1 Hz and modal damping ratios of around 1%, at least one hour is recommended.

The study of the simulated free decays illustrated the limitations of the exponential fitting and showed the potential of the SSI-COV method. It became clear that the use of this method in these tests provides very good results. However, this procedure has the limitation of providing modal damping estimates for levels of accelerations higher than the ones that occur during the normal use of the structures. These types of test have also the disadvantage of being more expensive and less practical than the ambient vibration tests.

It is important to refer that, in this paper only the errors that arise from the procedures used for the modal damping ratios identification were studied. However, in the identification of modal damping ratios of real Civil Engineering structures, there are other factors, related with the dynamic behaviour of the structures, which can explain the differences sometimes observed between the estimates provided by the two types of dynamic tests. The most important ones are: the variation of the modal damping ratios with the amplitude of the structural response and the influence of the wind characteristics on the observed modal damping ratios, leading to the existence of aerodynamic damping.

This simulation study will be followed by the reanalysis of data collected in Civil Engineering structures where both ambient and free vibration tests have been performed by the Laboratory of Vibration and Monitoring of the University of Porto (ViBest).

5 Acknowledgments

The Ph.D. Scholarship (SFRH/BD/24423/2005) provided by the Portuguese Foundation for Science and Technology (FCT) to the first author is acknowledged.

6 References

[1] F. Magalhães, E. Caetano and A. Cunha - *Operational Modal Analysis of the Braga Sports Stadium Suspended Roof*, IMAC XXIV, St. Louis, Missouri, USA, 2006

[2] F. Magalhães, E. Caetano and A. Cunha - *Dynamic Testing of the New Coimbra Footbridge before Implementation of Control Devices*, IMAC XXIV, Orlando, Florida, USA, 2007

[3] A. Cunha, F. Magalhães and E. Caetano - *Output-only Modal Identification of Luiz I Bridge before and after Rehabilitation*, ISMA 2006, Leuven, Belgium, 2006

[4] SVS - ARTeMIS Extractor Pro, Release 4.0. Structural Vibration Solutions, Aalborg, Denmark, 1999-2004

[5] LMSInternational - LMS Test.Lab. Leuven, Belgium, 2005

[6] A. Cunha and E. Caetano - *From Input-Output to Output-Only Modal Identification of Civil Engineering Structures*, IOMAC, Denmark, 2005

[7] R. Brincker, L. Zhang and P. Andersen - *Modal Identification from Ambient Responses Using Frequency Domain Decomposition*, IMAC XVIII, San Antonio, USA, 2000

[8] Peter Van Overschee and Bart De Moor - *Subspace Identification for Linear Systems*, Kluwer Academic Publishers, Leuven, Belgium, 1996

[9] Bart Peeters - *System Identification and Damage Detection in Civil Engineering*, PhD Thesis, Katholieke Universiteit Leuven, Leuven, 2000

[10] F. Magalhães - *Stochastic Modal Identification for the Validation of Numerical Models*, Master Thesis (in Portuguese), University of Porto, Porto, 2004

[11] P. Andersen, R. Brincker and P. H. Kirkegaard - *Theory of Covariance Equivalent ARMAV Models of Civil Engineering Structures*, IMAC XIV, Dearborn, USA, 518-524, 1996

[12] B. Peeters, G. De Roeck, E. Caetano and A. Cunha - *Dynamic Study of the Vasco da Gama Bridge*, ISMA 2002 International Conference on Noise and Vibration Engineering, Leuven, Belgium, 2002