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Estimation of damping ratios of steel structures by Operational Modal Analysis method

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ABSTRACT

In this study, it is aimed to compare the modal damping ratios attained by considering the measurement duration, frequency range, sampling rate, and the method used in modal parameter identification as variable parameters. The investigations were performed on a 3 storey steel building model. The measurements were taken from only top floor level of the building model by using twelve uni-axial seismic accelerometers. An impact hammer with rubber tip was used to vibrate the model by generating random impacts. The measurements were repeated by taking into account four different time intervals (5–10–30–60 min) using 0–12.5 Hz as the base frequency range. The collected signals were analyzed within 0–6.25 Hz frequency range considering the sampling rates as 512, 1024 and 2048. Both the natural frequencies and the modal damping ratios were obtained from each measurement by using Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI) techniques. The natural frequencies and their corresponding modal damping ratios were presented and compared with each other for all cases. It was observed from the study that the change in the natural frequencies was very small while the modal damping ratios were changed considerably depending on the selected analysis options.

1. Introduction

It is very difficult to predict the modal damping ratios of structures at the design stage, but they have a strong influence on the structural dynamic behavior. The amplitude of vibrations at resonance depends on these values inversely. Therefore, in structures subjected to any dynamic excitations, it is important to perform dynamic tests after construction to check the assumptions adopted during the design and eventually to implement solutions to reduce the vibrations. From many practical applications, it has been revealed that the damping ratio is equal to 5% for reinforced concrete structures and 2% for welded steel structures.

Ambient vibration test with Operational Modal Analysis (OMA) method is very powerful to estimate dynamic characteristics of structures because the method uses the available ambient excitation. Therefore, it is very economical and practical many kinds of structures from civil and mechanical engineering. Furthermore, the data are collected during the normal use of the structure and consequently the identified modal parameters are associated with realistic vibration levels. Although the available modal parameter identification techniques can provide very accurate estimates of natural frequencies and mode shapes, it is usually observed that the corresponding damping estimates present a significant scatter [1]. Papageorgiou and Gantes were presented a work that was to come up with equivalent modal damping ratios and used them in the analysis of irregularly damped structures [2]. Unlike the analytical estimation of Huang et al. [3], the modal damping ratios were extracted from a complex valued procedure and their validity in a real valued analysis procedure, not different from an ordinary everyday analysis, was then tested.

This paper presents the natural frequencies and the modal damping ratios of a steel building model for different data analysis options used in Operational Modal Analysis method. The investigations were carried out by taking into consideration the measurement duration, frequency range, sampling rate and analyze method as variable options. The study consists of a brief introduction and formulation about ambient vibration test and modal parameter estimation, the measurements on the selected model, the modal parameter identification for all cases and comparison of the natural frequencies and modal damping ratios. At the end of the study, some concluding remarks are also presented.

2. Ambient vibration test and modal parameter identification

In an ambient vibration test, the acceleration responses of structures excited by ambient loads are measured. Traffic loads, wind, extensive human activities, etc. are suitable to vibrate structures without interrupting daily usage. Operational Modal Analysis is used instead of classical mobility-based modal analysis for accurate modal identification

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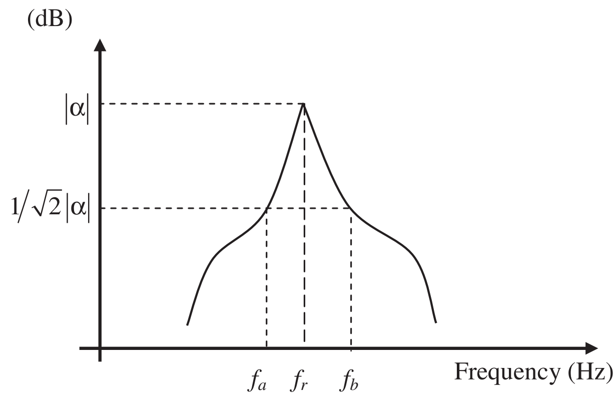

Fig. 1. A typical damping estimation by peak picking [10].

under actual operating conditions, and in situations where it is difficult or impossible to artificially excite the structure. The algorithms used in OMA assume that the input forces are stochastic in nature. This is often the case for civil engineering structures like buildings, towers, bridges and offshore structures, which are mainly loaded by ambient forces like wind, waves, traffic or seismic micro-tremors [4]. In some cases, the vibration level is low; so, the used accelerometers have to be very sensitive and specialized modal parameter extraction methods are needed.

Nowadays, there are several robust methods, working in time or frequency domains, which are already implemented in user-friendly software [5]. A review of the most commonly used methods in civil applications was presented by Cunha and Caetano [6]. In the present work, the modal parameter identification is based on the Enhanced Frequency Domain Decomposition (EFDD) method and the Stochastic Subspace Identification (SSI) methods. The first one is a non-parametric frequency domain method, whereas the second ones are parametric time domain methods [7, 8].

2.1. Enhanced Frequency Domain Decomposition (EFDD)

In the Enhanced Frequency Domain Decomposition (EFDD) technique, the modal estimation is divided into two steps. The first step is to perform the Frequency Domain Decomposition (FDD) Peak Picking. The second step is to use the FDD identified mode shapes to identify the Single-Degree-of-Freedom (SDOF) Spectral Bell functions [9]. The identification of the SDOF Spectral Bell is performed using the FDD identified mode shape as reference vector in a correlation analysis based on the Modal Assurance Criterion (MAC). Besides storing the singular values that describe the SDOF Spectral Bell, the corresponding singular vectors are averaged together to obtain an improved estimate of the mode shape. The average is being weighted by multiplying the singular vectors with their corresponding singular values. The natural frequency and the damping ratio of the mode are estimated by transforming the SDOF Spectral Bell to time domain. The main equation in the EFDD technique can be written as,

Table 1
The sectional properties of the structural members.

Properties	Columns	Beams	Girders	Braces
Section type	I120	I80	U65	ϕ 6
Cross sectional area (cm^2)	14.2	7.57	9.03	0.283
Moment of inertia (cm^4)				
Strong direction	328	77.8	57.5	6.36 ∗ 10 − 3
Weak direction	21.5	6.29	14.1	

$$[G_{\mathbf{yy}}(\omega)] = [H(\omega)]^{*}[G_{\mathbf{xx}}(\omega)][H(\omega)]^{T} \tag{1}$$

where $G_{\mathbf{xx}}$ is the Power Spectral Density (PSD) matrix of the input signal, $G_{\mathbf{yy}}$ is the PSD matrix of the output signal, H is the Frequency Response Function (FRF) matrix, and * and T denote complex conjugate and transpose respectively. After some mathematical manipulations, the output PSD matrix attained as,

$$\hat{G}_{yy}(j\omega_i) = s_i u_{i1} u_{i1}^{D} \tag{2}$$

where u_{ij} is a singular vector and s_{ij} is scalar singular values, respectively. Superscript D denotes complex conjugate and transpose. The first singular vector at the r-th resonance is an estimate of the r-th mode shape,

$$\hat{\phi}_r = u_{r1}. \tag{3}$$

The modal damping ratio is also estimated as,

$$\mathrm{n_r} = \frac{f_{\mathrm{a}}^2 - f_{\mathrm{b}}^2}{2 f_{\mathrm{r}}^2} = \frac{\Delta f}{f_{\mathrm{r}}} \tag{4}$$

$$\xi = 2 * \mathrm{n_r} \tag{5}$$

where f_{r} is the resonance frequency as shown in Fig. 1.

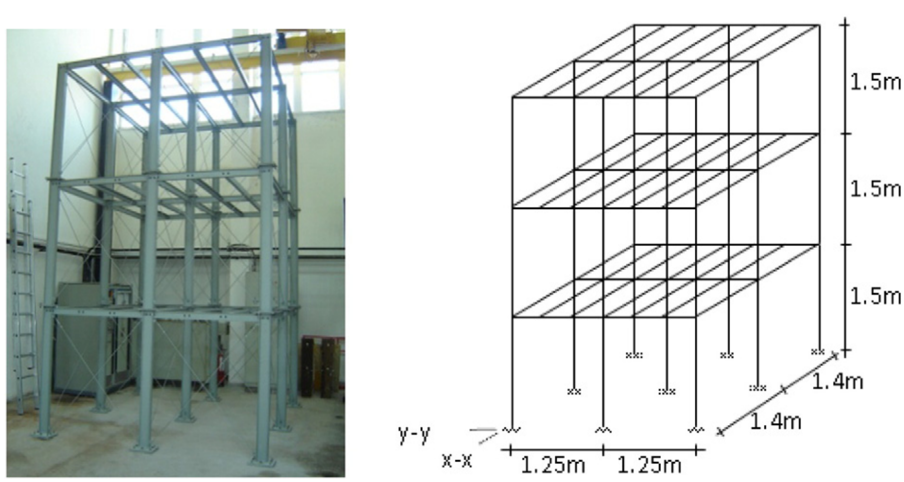

Fig. 2. The investigated steel building model and its dimensions.