Wandering of the modal parameters in existing building: application to structural health monitoring

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Abstract Ambient vibrations in building is of increasing interest for applications in mechanical engineering, civil engineering and earthquake engineering. With advances in data acquisition systems (number of measurement points, continuous recording, low-noise instrument) and advances in signal processing algorithms, further and better studies can be conducted on civil engineering structures for evaluating their modal parameters and their physical properties. This study is focused on long- and short-term variations of frequency in buildings. After a brief overview of the physical meanings and the practical interest for earthquake engineering, some examples are shown. They concerns the transient variations of modal parameters related with non-linear behavior of the system, the permanent decrease of frequency and damping after extreme event and the natural wandering of modal parameters, often related to atmospheric conditions. These changes, however, confirms the great stability and confidence measurements in buildings using modal analysis. This information helps to consider the relevancy of analysis of existing monitoring (damage, ageing, and so on) and can better calibrate the mechanical models used for the analysis of seismic vulnerability of existing structures, and thereby help reduce variability of their estimates.

1 Introduction

Since Omori [1], a large scientific community has dealt with the building frequency monitoring for structural and earthquake engineering (e.g., [2], [3], [4], [5], [6]). A critical step in seismic risk assessment is therefore to be able to predict the expected damage of a given earthquake in the existing structures. This may be of great interest to local or regional authorities in preparing for earthquakes, emergency response planning and risk mitigation. In the literature (see [7] for a complete review), the first vulnerability methods were developed in strong seismic regions which had already suffered destructive earthquakes. They were based on post-seismic inventories used to adjust continuous (vulnerability functions (VF)) or discrete (damage probability matrices (DPM)) functions of seismic damage. The fragility curves approach is thus very well suited to the current assessment of seismic hazard (probabilistic or deterministic) based upon instrumental ground-motion measures and includes all uncertainties (including hazard and vulnerability) for evaluating regional seismic risk. However, for the existing buildings, the adjustment of structural models must assume a large set of unknown parameters influencing the response of such buildings and introducing a large range of errors and epistemic uncertainties, generally due to the lack of structural plans, ageing and structural design. One solution to reduce these epistemic uncertainties is to perform ambient vibration tests in buildings, providing an estimate of the elastic modal parameters of structures (resonance frequencies, damping ratios and modal shapes).

Over the last two decades, ambient vibration (AV) methods for assessing the modal parameters of existing structures have received considerable attention. Since the design forces and displacements in structures are frequency and damping dependent (based on the seismic coefficient C(T,?) where T is the period of the building and ? is the damping ratio), the use of AV methods provides relevant information on the elastic characteristics of the building at relatively low cost. Since the beginning of the 20th century, there has been an abundance of scientific literature on the interests of such experiments, which have been widely used by civil engineering, engineering seismology and earthquake engineering communities to monitor structures, to calibrate the elastic properties used by modellers, to compare building response under weak and strong motions and to estimate seismic damage after strong earthquakes.
Since the first ambient vibration experiments, efforts have been made on signal processing methods, known as modal analysis methods, as well as on the development of acquisition systems to improve recording quality. With these new instruments and new signal processing, recent studies (e.g., [8], [9]) have shown how ambient vibrations could be used for detecting variations for structural health monitoring with special focus on the permanent and transient decrease of the frequency value during ground shaking. The damaging process during earthquakes produces a permanent loss of structural stiffness and thus a permanent decrease of the fundamental frequency. Farrar et al. [10] mentioned that frequencies are probably the modal parameters most sensitive to change, particularly because the loss of stiffness directly impacts the frequency values. Nevertheless, the apparent damping coefficient recorded in the building may also be directly sensitive to a local loss of stiffness (e.g., [11], [12]) or to soil-structure interaction (e.g., [13]).
The main goal of this paper is to illustrate the use of frequency and damping variations for detecting changing in existing building, related with its integrity. After a brief reminder concerning the dynamics of structures, examples of transient changing during strong motion and long-term wandering of modal parameters under ambient vibrations are discussed.

2 Dynamics of structures: frequency and damping

After Clough and Penzien [14], the main objective of a structural dynamics study is "the determination of the structural response to a dynamic load, i.e. the resulting stresses and deflections, under a given load whose its magnitude, direction and/or position varies with time. "
All structures are subjected to dynamic loads during their lifetime. A distinction is done concerning several types of loading: (1) random loads such as those produced by wind or earthquakes, and which are described generally in a statistical way; (2) deterministic loads for which the amplitude, direction and point application are known. This second category can be produced by a rotating machine (periodic charge) or a short-term impact (non-periodic load). Each type of loading has a formulation and a particular solution method. The response of a structure subjected to dynamic loading is obtained by solving the dynamic equations of motion. One must consider the constitutive equations, boundary conditions and initial steady-state system. Several solution methods are available in the literature ([14]), only the basics will be recalled here, oriented to provide an understanding of the processes to be

considered in the structural health monitoring.

Ambient vibrations (AV) in buildings are random loads. They are produced by the wind (low frequencies ¡1 Hz), internal sources (machinery, lift at high frequencies) and seismic noise (broadband). For example, the City-Hall building of Grenoble is permanently monitored by accelerometric stations as part of the National Building Array program of the French Accelerometric Network (RAP, http://www-rap.obs.ujf-grenoble.fr; [15]). Accelerometric sensors (EST-FBA) at the top of the building record vibrations continuously (sample rate 125 Hz) and transmit the data in real time to the RAP National Data Centre hosted at the Institute of Earth Science (ISTerre, Grenoble). By plotting the amplitude of the vibration for one month (Figure 1), we observe the close relationship between the building vibrations and the human activity. The amplitude of the motion increases during the day and decreases during the night and week-end and holiday are clearly observed on the amplitude of the signal.

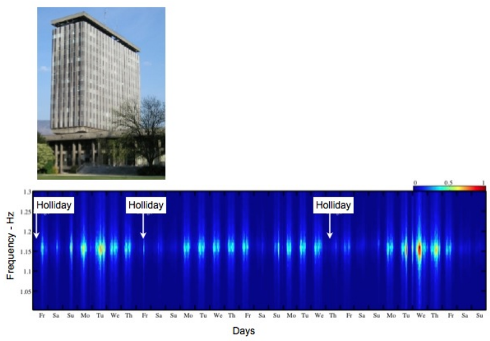

Figure 1: Fourier transform of the ambient vibrations recording at the top of the City-Hall building of Grenoble during May 2009 (after [16]).

Most studies of dynamics are then to represent a structure with an oscillator that will be more complicated than the desired analysis will be. One generally speaks of degrees of freedom (DOF): the number of degrees of freedom in a dynamic system expresses the smallest number of coordinates needed to define the position of all bodies of the system. In most cases, this simplifies the maximum number of DDL neglecting components of the motion so that we can model a complex system apparently with a reduced number of DOF.

In the simplest model of a structural dynamic analysis for earthquake engineering application, the building is considered as a Single-Degree-of-Freedom (SDOF) system, i.e. its essential physical properties such as its mass, elastic properties (stiffness) and energy-loss mechanism (damping) are assumed to be concentrated in one element (Figure 2). The structural response of such system (free vibrations) can be expressed by :

$$m\ddot{u}^t + c\dot{u} + ku = 0 \qquad (1)$$

where m, k and c are the mass, stiffness and energy-loss mechanism of the building and u, $\dot{u}$ and $\ddot{u}$ are displacement, velocity and acceleration of the building. After dividing by

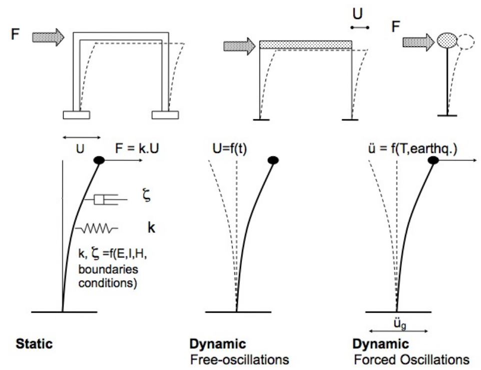

Figure 2: Single-degree-of-freedom (SDOF) representation of buildings for earthquake engineering activities. The mass, elastic properties (stiffness) and energy-loss mechanism (damping) are assumed to be concentrated in one element, represented by a concentrated mass where the inertia force produced by seismic ground motion is applied.

m and solving this equation, we obtain the elastic modal parameters of the systems, such as:

$$\omega = \sqrt{\frac{k}{m}} \qquad (2)$$

$$\zeta = \frac{c}{2\omega m} \qquad (3)$$

where $\omega = 2\pi.f$ is the resonant circular frequency of the building and ζ represents critical damping of the system. Similarly, we can show that, considering a Multi-Degree-Of-Freedom system (MDOF), the shape of the frequency-response curve at each mode is controlled by the system's damping coefficient and the modal frequency. The free-oscillating response of the MDOF, as controlled by the $e^{-\zeta\omega t}$ function for each mode, is thus proportional to the frequency ω and the critical damping coefficient ζ.

Since we assume that the mass m remains constant during the building lifetime, the frequency and damping variations that could be observed are then related to the variation of stiffness k, k depending on the properties of the building (e.g., Young's modulus, height, design of the building, etc.), but also on the cracks opening and the boundary conditions (e.g., fixed- or flexible-base building) influencing by the soil-structure interaction. Frequency analysis is currently included in building tests since the simple Fast-Fourier Transform of ambient vibrations recorded at the top of the building provides relevant information on the modal frequencies, above all for very tall buildings exhibiting a good signal-to-noise ratio and a low damping.

3 Case 1: non-linear behavior of building

The physical meaning of instantaneous frequency variation is a crucial point that must be explored in depth since the monitoring of building frequency is certainly the easiest way for building behavior assessment and health monitoring. A large set of methods using the time-frequency representation exists for monitoring building frequency variations during earthquakes. The analysis of the smallest frequency variations under strong and weak motions must be sufficiently precise in order to understand their physics and consequently, to detect damages or changes.

The reassignment procedure for the Smoothed Pseudo Wiegner-Ville (SPWV) distribution ([17] significantly increases the resolution to analyze the transitory variations of frequencies in buildings. For example, during the San Fernando earthquake (magnitude M=6.6, on February 9, 1971), the motion recorded at the top of the Millikan Library building, certainly one of the first instrumented and extensively studied buildings in the world, illustrates the effect of the non-linear behavior of existing building. We observe (Figure 3) a rapid decrease in the first frequency during the first 15 s. The pre-seismic frequency is greater than 1.3 Hz, but due to the very short pre-event time window, this frequency cannot be clearly seen in this figure. The co-seismic frequency, i.e., the minimum value reached during the earthquake, is 0.94 Hz, i.e., a transitory drop of 35% with respect to the pre-seismic frequency value (1.45 Hz) found in [8]. This co-seismic frequency occurs 5 s after the peak acceleration. Once this value is reached, the frequency increases gradually up to the post-seismic frequency (frequency at the end of the recording) and equal to 1.15 Hz. This post-seismic frequency is close to the value obtained after the San Fernando earthquake by forced and weak vibration tests performed in 1974 (1.21 Hz) (Clinton et al., 2006). This earthquake produced cracking and spalling of the concrete slabs on the ground floor and horizontal cracks in the core shear walls between the basement and the second story in the N-S direction. The transient decrease of the frequency during shaking is then related to the opening-closing process of the existing cracks in reinforce concrete elements.

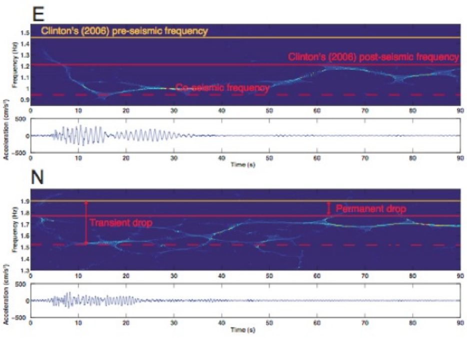

Figure 3: Time-frequency analysis of the recording obtained at the top of the Millikan library during the San-Fernando earthquake (1971). The distribution is obtained using the Reassigned method applied to the Smoothed Pseudo Wiegner-Ville method. The yellow line corresponds to the frequency of the building before the earthquake and the red dashed lines correspond to the co- and post-seismic frequencies of the building (after [17]).

Similar observation can be done during the Martinique earthquake (Mw 7.4) that occurred on November 29, 2007 (Figure 4). The CDST building (*Centre de Decouverte des Sciences de la Terre*) in Martinique, designed on isolating rubber bearings, resisted the 2007 earthquake (Mw=7.4). We can see that during the strong shaking, at a certain level of shaking, non-linearity appears, reflected by incursions below the lowest elastic mode. Over the highest energy part of the signal, frequencies of around 1.2Hz were recorded, which is the result of the degradation of the rubber's elastic module.

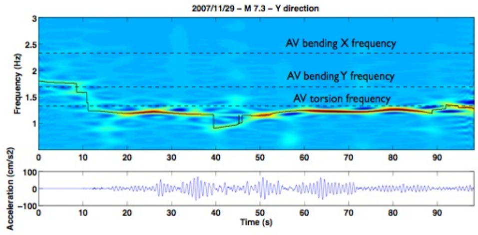

Figure 4: Time-frequency analysis of the recording obtained in the CDST building during the Martinique earthquake (Mw=7.4; 2007). The distribution is obtained using the Reassigned method applied to the Smoothed Pseudo Wiegner-Ville method. The black dashed lines correspond to the bending and torsion frequencies of the building before the earthquake, obtained using modal analysis.

4 Case 2: damage detection

Many papers have discussed the fundamental frequency sensitivity in the case of damage after an extreme event. Most studies are based on the Fourier analysis or the time-frequency analysis of the recorded data. For this reason, monitoring the frequency of buildings may be useful to detect the damage after earthquakes, as recently shown in practice by Dunand et al. [?] after the Boumerdes, Algeria (May 21, 2003) earthquake. In most cases, after damaging earthquake, a group of expert tags the buildings with paints, considering the degree of damage (green: the building is safe; orange: the building is unsafe but further analysis should be done; red: the building is certainly unsafe and it must be destroyed). The damage screening is done visually on the field and rapidly just after the main shock in order to define if the buildings can be re-occupied by the inhabitants or not. In this case, a large set of building having (or not) suffered strong damage was tested using ambient vibrations. One record done at the top of each building was done, and the Fourier transform computed. Because no information was available before the earthquake, we have considered the undamaged buildings as the pre-earthquake information, blocks of urbanization being composed by buildings having the same characteristics (size, type of material, age of construction...). The variation of the frequencies observed after the earthquake provides information on the integrity of the buildings (Figure 5). In some case, the most damaged buildings had a decrease of their frequency of about 70% while the green buildings (considered as safe) had a decrease of 30% in some cases. This experience showed how the reducing frequency observed after a strong event can help for the decision making.

5 Case 3: long-term variation of frequency and damping

An effective solution to track frequency and damping variations over time is to apply the random decrement

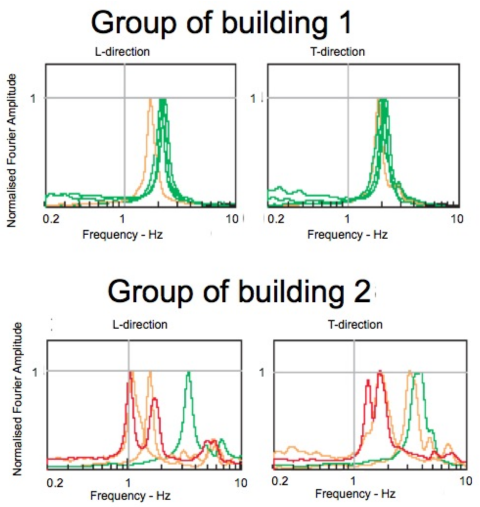

Figure 5: Frequency variation of the buildings having suffered any, moderate or strong damage during the Boumerdes earthquake (2003). Fourier transform were obtained suing ambient vibration recorded at the building top. Green curves correspond to building having been tagged as no damaged, orange curves to buildings with moderate damage and red curves to strongly damaged buildings. Representation are done by group of building having the same characteristics (size, design, age of construction ....) (after [**?**]).

technique, RDT. This method was first proposed by Cole in 1973 and is based on the fact that, at any given time, ambient vibrations contain a random and impulse element. By stacking a large number of windows with identical initial conditions, ambient vibrations remain stationary and the impulse response of the structure is revealed. Vandiver et al. [19] and Asmussen et al. [20] provide details on the theory of RDT and its mathematical formulation that can be simplified by:

$$RDT(\tau) = \frac{1}{N} \sum_{i=1}^{N} s(t_i + \tau) \tag{4}$$

where N is the number of windows with fixed initial conditions, s is the ambient vibration window of duration τ, and ti is the time verifying the initial conditions. The choice of initial conditions is a key point in ensuring the stability of the Random Decrement signature.

This method is applied to the Mont-Blanc (MB) and Belledonne (BD) buildings, two of the three Ile Verte towers located in Grenoble (France)(Figure 6). These stand-alone towers are 30-storey reinforced concrete buildings. Ambient vibrations were recorded simultaneously at the top of the two towers during one month using a 24 bit A/D CityShark acquisition system [21] connected to a 5-s Lennartz 3C velocimeter. Continuous recording was performed and recording files were divided into one-hour long time windows sampled at 50Hz. The acquisition systems in the two buildings were completely independent. The behavior of the two buildings is quite similar, their fundamental mode being at 0.67Hz (T) and 0.89Hz (L), and 0.65Hz (T) and 0.84Hz (L) for the BD and MB buildings, respectively. All these values were observed by Michel et al. (2011) using extensive modal analysis, with multi-channels recordings. Herein, only the fundamental mode was used to test the RDT. The long-term variations of frequency and damping were then computed hourly from the RDT, i.e. for time-windows greater than 1000 periods. Frequency fluctuations are shown in Figure 6 for one month and for the two buildings and the two horizontal directions. Near-perfect synchronization was observed in the frequency variations between the two buildings, RDT being able to detect very small fluctuations (less than 0.1%). Stronger transient variations, such as between the 10th and 11th of August, were also observed for the two buildings. Since the buildings are completely independent, the origin of these variations must be physical and directly related to different building stiffness or boundary conditions. Mikael ([16] showed that correlations with the daily variations are clear and longer period of variations are also observed, such as during the second week of August. The same trend was previously observed by Clinton et al. (2006), i.e. frequency increases with temperature. The scientific explanation for frequency variations has not yet been completely understood but it may result from the expansion of concrete or cladding in relation to sun exposure, as the difference between the NS and EW faces of the building having different behavior.
RDT is also used for long-term monitoring of the damping value (Figure 7). No clear variations are observed, although the stability of the measurement may reflect the efficiency of RDT for damping estimation. One conclusion could be that damping is less sensitive to external conditions. In contrast to results obtained with stronger motion (e.g., [11], [22]), the frequency and damping are not clearly correlated at these levels of excitation, regardless of the building and the direction.

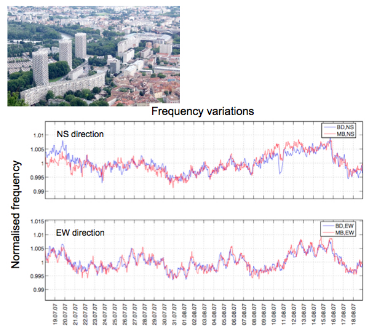

Figure 6: Frequency variation of the Mont-Blanc MB and Belledonne BD towers computed using the Random Decrement Technique based on ambient vibration recordings (after Mikael et al., 2012).

6 Conclusion

Structural Health Monitoring of existing buildings has gained more importance for the last two decades because of the complexity of buildings for modelling, the ageing of dwelling buildings and industrial infrastructures and the needs of integrity assessment of structures such as after extreme events. Recent papers have shown the sensitivity of modal parameters (damping and frequency) to external forcing and boundary conditions such as temperature, wind and soil-structure interaction.

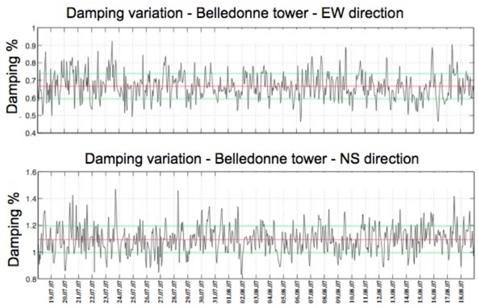

Figure 7: Damping variation of the Mont-Blanc MB and Belledonne BD towers computed using the Random Decrement Technique based on ambient vibration recordings (after Mikael et al., 2012).

A significant amount of research has been conducted in the area of non-destructive damage evaluation (NDE) via changes in the dynamic modal responses of a structure. The basic idea is that modification of stiffness, mass or energy dissipation characteristics of a system may alter its dynamic response, as shown in this paper during the San Fernando, Martinique or Boumerdes earthquake. The variation of these modal parameters are often due to the opening/closing process of cracks, changing the global Young's modulus of the building. Up to date, the methods developed for NDE can be classified into three levels.The first level LV1 is to detect if changes has occurred. Most of this method were based on the Fourier analysis or time-frequency distribution of recordings obtaining within a building during or after extreme events. The most abundant literature is concerned by the earthquake engineering, within the framework of the 60's US program of building network, for which earthquake data were collected and processed for understanding the variations of the modal parameters during and after earthquakes, related with the shaking level and the damage observed. The second level (LV2) is to detect if changes has occurred and simultaneously determine the location of damage. This level requires recordings at several places in the buildings for defining the mode shapes and the frequencies of the structure, both modal parameters being using to identify the origin of the variations observed. The third level (LV3) is to detect if changes has occurred, determine the location of damage as well as estimate the severity of damage. Few application of LV3 are available in practice, while the estimate of the severity may contribute significantly to the action of the decision-makers in case of emergency after extreme event.

While the first applications of NDE were focused on the understanding of the data and observation, the second phase of the activities was focused on developing practical theories of damage detection to simultaneously predict the location of damage (LV2) and estimate the geometric size of damage in structures (LV3). A need remains to be able of measuring only limited modal information in practice, such as using only one sensor at the top of the buildings, and the accuracy of changed being able to be detected as well, in relation with structural health.

The scientific interests of large-scale instrumentation and monitoring of existing buildings are then the monitoring of the structure in time, the assessment in changing the physical properties of structures between before and after earthquake for seismic damage assessment and the understanding of the building response to external shaking. Recent initiatives started, taking advantages of the reducing cost of news instruments (such as MEMS sensor, Micro-Electro-Mechanical Systems) for increasing the number of buildings monitored (QCN, [23] or using remote assessment of building frequencies with Lidar techniques [24].

Acknowledgments

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