Continuous Monitoring of High-Rise Buildings Using Seismic Interferometry

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Abstract  The linear seismic response of a building is commonly extracted from ambient vibration measurements. Seismic deconvolution interferometry performed on ambient vibrations can be used to estimate the dynamic characteristics of a building, such as its shear-wave velocity and its damping. The continuous nature of the ambient vibrations allows us to measure these parameters repeatedly and to observe their temporal variations. We used 2 weeks of ambient vibrations, recorded by 36 accelerometers that were installed in the Green Building at the Massachusetts Institute of Technology campus, to monitor the shear wavespeed and the apparent attenuation factor of the building. Because of the low strain of the ambient vibrations, we observed small speed changes followed by recoveries. We showed that measuring the velocity variations for the deconvolution functions, filtered around the fundamental-mode frequency, is equivalent to measuring the wandering of the fundamental frequency in the raw ambient vibration data. By comparing these results with local weather parameters, we showed that the air humidity is the dominating factor in the velocity variations of the waves in the Green Building, as well as the main force behind the wandering of the fundamental mode. The one-day periodic variations are affected by both the temperature and the humidity. The apparent attenuation, measured as the exponential decay of the fundamental-mode waveforms, is strongly biased due to the amplitude of the raw vibrations and shows a more complex behavior with respect to the weather measurements. We have also detected normal-mode nonlinear interaction for the Green Building, likely due to heterogeneity or anisotropy of its structure. We found that the temporal behavior of the frequency singlets may be used for monitoring.

Introduction

Seismic interferometry is a technique used to re-datum a source or sources recorded by two receivers to the location of one of the receivers, and then retrieve the wave propagation between the two receivers only (e.g., Snieder et al., 2006; Wapenaar and Fokkema, 2006; Schuster, 2009). Seismic interferometry has been applied in several fields of seismology to create an image of the subsurface at different scales with surface waves (Shapiro et al., 2005; Lin et al., 2008; Picozzi et al., 2009; Mordret et al., 2014, 2015) or with body waves (Wapenaar et al., 2008; Draganov et al., 2009). When used with ambient vibrations (the so-called seismic noise), seismic interferometry has allowed seismologists to continuously monitor geological targets. Indeed, ambient vibrations can be recorded virtually continuously, and everywhere on Earth; therefore, a repetitive utilization of seismic interferometry can be performed to follow the variations in time of the seismic-wave propagation between pairs of receivers. This monitoring method has been developed originally to monitor volcano pre-eruptive behavior (Sens-Schönfelder and Wegler, 2006; Brenguier, Shapiro et al., 2008; Mordret et al., 2010; Anggono et al., 2012) and crustal effects of large earthquakes (Brenguier, Campillo et al., 2008; Wegler et al., 2009; Minato et al., 2012; Froment et al., 2013; Brenguier et al., 2014).

In civil engineering applications, seismic interferometry was first introduced as a normalized input–output minimization method by Kawakami and Haddadi (1998), Kawakami and Oyunchimeg (2003), and later generalized by Snieder and Şafak (2006) to compute the time-domain impulse response function (IRF) of the Millikan Library in Pasadena, California. The technique has become very popular since then (e.g., Kohler et al., 2007; Todorovska and Trifunac, 2008a,b; Todorovska, 2009; Ebrahimian et al., 2014; Rahmani et al., 2015). The aforementioned studies use earthquake records as input excitation to determine the dynamic characteristics of the buildings. Because of the random and isolated occurrence of earthquakes, these signals are not well suited for continuous monitoring of civil structures (Nakata...
The use of ambient vibrations, on the other hand, is appropriate for the monitoring of these structures. Ambient vibrations can be recorded anywhere and at any time, and they have been used for building monitoring purposes through the measurement of the wandering of the modal frequencies (e.g., Clinton et al., 2006; Nayeri et al., 2008; Ditommaso et al., 2010; Mikaël et al., 2013). These studies showed that this parameter is very sensitive to irreversible changes in building structure, such as defects and cracks caused by earthquakes. It is also sensitive to reversible variations, such as ambient temperature or changes in humidity.

Prieto et al. (2010) showed that seismic interferometry could also be applied to ambient vibrations to retrieve the impulse response of a building. More recently, Nakata and Snieder (2014) used seismic interferometry on ambient vibration data to develop a continuous monitoring technique. Their time resolution of four days and the arrival-picking technique they used were not appropriate to draw any kind of conclusion about the potential causes of the observed shear-wave velocity variations inside the building. In this article, we extend the idea proposed by Prieto et al. (2010) and Nakata et al. (2015) to show that with a finer temporal resolution of 6 hours, along with more accurate seismic-velocity-variation-tracking techniques, we are able to finely measure the relative velocity variations inside the Green Building (Massachusetts Institute of Technology campus, Cambridge, Massachusetts), as well as its apparent attenuation variations. These temporal changes are then correlated with different local weather parameters, such as the temperature and humidity, to infer which one has a more significant effect on the building.

Data and Methods

We used 15 days of data (between 12 and 27 May 2015), continuously recorded on 36 accelerometer channels deployed inside the Green Building. The Green Building (Fig. 1a), currently the tallest building in Cambridge, was designed by I. M. Pei and constructed during the 1962–1964 period. It has an elevation of 83.7 m with a footprint of 16.5 m by 34 m. Mechanical rooms are located on the top two floors (i.e., nineteenth and twentieth floors). Heavy meteorological and radio equipment is asymmetrically mounted on the roof (Fig. 1b). Three elevator shafts are located on the eastern side of the building (Fig. 1c), and two stairwells are placed symmetrically at the northeast and northwest corners of the building. The building is constructed of cast-in-place reinforced concrete. The eastern and western facades are composed of 25-cm-thick shear walls that run the height of the building. The thickness of floor slabs is typically 10 cm. The basement floor has a depth of 3.8 m below the grade. Taciroglu et al. (2016) showed that the building’s dynamic behavior can be modeled by a simple shear beam. More detailed descriptions of the building’s characteristics can be found in Çelebi et al. (2014), Taciroglu et al. (2016), and Sun et al. (2017), in which the sensor information and deployment are also given. The sensor array was designed for monitoring the north–south and east–west translational vibration, the torsion, and the base rocking motion. The sensor locations and orientations are shown in Figure 1a. The sensors are installed below the floor slabs. Figure 1c illustrates the sensor locations at a typical floor. Because of these locations, the acceleration in each direction (\(a_0\) for east–west direction, \(v_0\) for north–south direction, and \(\theta_0\) for torsional direction) needs to be decoupled and is computed using the following equations:

\[
\begin{align*}
    u_1 &= u_0 - \theta_0 v_1 \\
    v_1 &= v_0 + \theta_0 x_1 \\
    v_2 &= v_0 + \theta_0 x_2.
\end{align*}
\]

in which \(u_1\) is the measured acceleration along the east–west direction; \(v_1\) and \(v_2\) are the measured accelerations along the north–south direction close to the eastern and western shear walls, respectively; and \(x_1\), \(x_2\), and \(y_1\) are the sensor coordinates in the \(x-O-y\) coordinate system with \(O = (0, 0)\), as shown in Figure 1c (see table I in Sun et al., 2017, for the numerical values of the station coordinates). Therefore, the decoupled accelerations are as follows:

\[
\begin{align*}
    \theta_0 &= \frac{v_1 - v_2}{x_1 - x_2} \\
    u_0 &= u_1 + \theta_0 v_1 \\
    v_0 &= \frac{x_2 v_1 - x_1 v_2}{x_2 - x_1}.
\end{align*}
\]

Figure 2 shows the spectrogram of the decoupled north–south acceleration recorded on the roof of the Green Building. The fundamental mode is observed as a constant spectral peak at 0.75 Hz, the first overtone at 2.55 Hz, the second overtone at 5 Hz (Çelebi et al., 2014), and the third overtone around 6.6 Hz. The daily pattern of man-made ambient noise, with higher amplitudes during working hours and smaller amplitudes during nights, is obvious. The two weekends with smaller noise amplitudes are also well observed (16–17 and 23–25 May, including Memorial Day).

Preprocessing and Impulse Response Functions from Deconvolution Interferometry

Before combining the data from the different sensors and applying deconvolution interferometry, the records from individual channels are preprocessed to mitigate potential biases introduced by the non-stationarity of the recorded ambient vibrations. The raw data are high-pass filtered at...
in which \( D_{U_x}(z, z_0, t) \) is the deconvolution function for vibration type \( U \) (\( U \) being the Fourier transform of either \( \theta_0 \), \( u_0 \), or \( v_0 \)) between floors at elevations \( z_0 \) and \( z \). \( n \) is the index of the 20 min segment \( (n = 1, \ldots, 2159 \text{ in this study}) \), and \( t \) is the lag time. In the right side of equation (7), \( \mathcal{F}^{-1} \) is the inverse Fourier transform, \( \omega \) is the angular frequency, \( \ast \) is the complex conjugate, \( \langle |U_n|^2 \rangle \) is the average power spectrum of \( U_n \), and \( \alpha = 0.5\% \) is a regularization parameter stabilizing the deconvolution (Nakata and Snieder, 2014). An estimation of the building response function \( D_U(z, z_0, t) \) is given by the average of the deconvolution functions over the two weeks:

\[
D_U(z, z_0, t) = \frac{1}{N} \sum_{n=1}^{N} D_{U_x}(z, z_0, t). \tag{8}
\]

We tested different preprocessing parameters, with an amplitude threshold of 1.5 standard deviations instead of 3, a high-pass filtering at 0.1 Hz instead of 0.05 Hz, and \( \alpha = 10\% \) in equation (7). We observed that the different preprocessing approach had only a marginal effect on our results, both for the velocity-variation measurements and for the damping variation measurements. Figure 3 shows the central part of the estimated IRFs for the north–south translational modes (Fig. 3a–d), the east–west translational modes (Fig. 3b–e), and the torsional modes (Fig. 3c–f). These estimations were done both in the time domain and in the frequency domain for each floor, with a source at the ground level. We can clearly observe a wave pulse traveling up and down in the building, with varying speeds, depending

\[
D_{U_x}(z, z_0, t) = \mathcal{F}^{-1}\left(\frac{U_n(z, \omega)U_n^*(z_0, \omega)}{|U_n(z_0, \omega)|^2 + \alpha\langle |U_n(z_0, \omega)|^2 \rangle}\right).
\tag{7}
\]
on the type of vibration (the dashed lines are for reference only, assuming a constant speed of 365, 320, and 600 m/s for the north–south translational modes, east–west translational modes, and torsional modes, respectively). These pulses result from the superposition of all normal modes of the building, and their frequency spectra are discrete. At longer times, only the resonance of the fundamental modes is visible because the fundamental mode attenuates more slowly (Snieder and Şafak, 2006; Fig. 4a). We observe a clear symmetry between the negative and positive lag times of the IRFs, both in phase and amplitude. Although given seismic interferometry theory, the phase symmetry is expected, this should not be the case for the amplitudes because the attenuation always follows causality. The amplitudes should therefore increase with increasing negative lag times (Snieder, 2007). The presence of ambient vibration sources inside the building may play the role of volumetric sources and balance the amplitudes at negative lag times (Snieder, 2007).

Another way to measure the speed of the traveling waves inside the building is by looking at the deconvolution functions between the roof and the other floors, with the source on the roof. In this configuration, Snieder and Şafak (2006) and Rahmani and Todorovska (2013) showed that the deconvolution functions are the superposition of an acausal upward-moving wave with a causal downward-moving wave. The speed of these waves is the shear wavespeed of the building for a pure shear-beam building. In the case of the Green Building, the pure shear-beam model is not completely valid, as indicated by the ratios of the higher-mode

Figure 3. Estimated impulse response functions (IRFs) of the Green Building, filtered between 0.5 and 7.5 Hz. (a) Waveforms of the north–south translational modes at each floor from a source at the ground level. (b) Same as (a) for the east–west translational modes. (c) Same as (a) for the torsional modes. The gray dashed lines in (a), (b), and (c) show the travel time of the shear-wave traveling up and down inside the building at the constant speed of 365, 320, and 600 m/s for the north–south translational modes, east–west translational modes, and torsional modes, respectively. Note that the waves reflect at the basement level with a negative reflection coefficient. (d), (e), and (f) show the power spectra of the waveforms shown in (a), (b), and (c), respectively.

Figure 4. (a) Estimated north–south translational IRF of the Green Building between the ground level and the roof (with the source at ground level), filtered between 0.5 and 7.5 Hz (black) and between 1.5 and 7.5 Hz (gray) to remove the fundamental mode. The inset is a zoom on the central part of the IRF. Note that at large lag times, high frequencies are attenuated, and only fundamental-mode energy remains. (b) Fourier transform of the north–south translational IRF showing the transfer function of the north–south translational building motion. The four first modes are observable, and their frequencies are shown.
frequencies \(f_i\) over the fundamental-mode frequency \(f_1\). These ratios are not in accordance with the sequence \(f_i/f_1 = [1, 3, 5, 7, \ldots]\) (Fig. 4b). Some bending occurs during the building deformation, which leads to the dispersion of the shear waves that propagate within the building (Ebrahimian and Todorovska, 2013). The speed of the waves shown in Figure 5 is therefore the frequency-dependent phase velocity. We note a discrepancy between the velocity of the north–south modes measured with the source on the ground floor and the source on the roof. This could also be due to dispersion or reflections caused by the internal structure of the building (Snieder and Şafak, 2006; Rahmani and Todorovska, 2013). In this framework, the IRF is not a superposition of modes but a broadband pulse having a continuous frequency spectrum. According to the shear-beam model of Rahmani and Todorovska (2013) and Snieder and Şafak (2006), the upward-moving and downward-moving pulses vanish at ground level and are not sensitive to the soil–structure interaction. Moreover, the wavelength of the waves (on the order of 100 m) is much larger than the typical floor height, so the scattering inside the building should be minimal. However, at low frequency, we observe an upward-moving wave in the east–west direction (Fig. 5b), which could be a spurious arrival due to internal vibration sources within the building that are not completely canceled by the deconvolution process. At higher frequencies, a clear coda follows the main pulse. This coda may be the consequence of the superposition of multiple reflections at the base and inside the building, with spurious waves generated by sources within the building (as well as the side lobes of the bandlimited impulsive source) (Fig. 5d; Rahmani and Todorovska, 2013; Todorovska and Rahmani, 2013).

Velocity-Variation Measurements

For monitoring applications, the absolute value of the velocity is not needed; only the relative velocity variations are necessary. The fact that the waves are dispersive does not affect the relative velocity-variation measurements. Because this is the case, it is possible to use techniques that are much more accurate than picking the absolute travel times of seismic pulses propagating inside the building. The basic principle that can be used to measure relative seismic-velocity variations \(dv/v\) involves the comparison of a current wave-
form to a reference one by measuring their relative phase shifts along the lag time. Here, the current waveforms are the individual $D_{\mu s}$ waveforms averaged in a 6-hr moving window (average of the $r$th deconvolution function with the 35 previous ones), and the reference one is $D_{\mu r}$. We used two common techniques to measure $dv/v$ within the Green Building: (1) the moving-window cross-spectral (MWCS) technique (Clarke et al., 2011), which is performed in the frequency domain, and (2) the stretching technique (ST; Sens-Schönfelder and Wegler, 2006; Hadziioannou et al., 2009), which is performed in the time domain. The comparison of the results from both independent methods allows us to assess the accuracy and consistency of our measurements (Mordret et al., 2016).

The IRFs deconvolved by the ground floor present two distinct types of vibration: (1) the propagating part at short lag times ($−3 \lesssim t \lesssim 3$ s), where the fundamental mode and the overtones are superposed, and (2) the resonant part at large lag times ($−25 \lesssim t \lesssim −6$ s and $6 \lesssim t \lesssim 25$ s), where the fundamental mode dominates. We chose to analyze these two kinds of vibrations separately. The MWCS technique is performed within the previously described time windows using small sliding windows, with a length six times the central period of interest. The small windows move with 0.1 s steps. For each small window, the cross spectrum between the current and the reference waveform is computed. From this cross spectrum, the coherence and the phase between the two signals, as a function of the frequency, is extracted. A weighted linear regression (weighted by the coherency) is performed on the phase in the frequency band of interest to extract the phase delay between the reference and current correlation, as well as an error estimate of the slope. Thus, for each small sliding window, we obtain three values: a time delay $tdelay$ (in seconds), an error for the time delay $errtdelay$ (in seconds), and the average coherency between the two signals $coh$. Then, these measurements are used in a second step to evaluate the relative velocity variation $dv/v = −dt/t$ between the reference waveform and the current waveform. A weighted linear regression on the time delays with respect to the central time of the windows is used to calculate the final $dv/v$ value and its uncertainty for a specific frequency band. Only the time delays with errors $errtdelay < 0.03$ s and coherency $coh > 0.8$ are used in the final linear regression to estimate $dv/v$. The uncertainty on the linear regression is taken as a function of the uncertainties of the relative velocity variations.

The ST is based on the assumption that if a small velocity change occurs homogeneously in the medium, the current waveform will simply be a stretched or compressed version of the reference waveform. The stretching coefficient is therefore the relative velocity variation $d\mu/v$. Prior to the stretching measurement, the reference and current waveforms are filtered in the frequency band of interest. The measurement is performed using a grid search on the stretching coefficients. We sampled 300 stretching coefficients, linearly spaced between $−5\%$ and $5\%$. For each coefficient, the time axis of the current waveform was stretched, and then the current waveform was interpolated onto this new time axis. The correlation coefficient between the window of the stretched current waveform and the reference waveform was then computed and stored. The best $dv/v$ measurement was chosen as the stretching coefficient that maximized the correlation coefficient between the current stretched and reference waveforms. To refine the estimation of $dv/v$, we used the maximum correlation coefficient and its nearest left and right neighbors. We performed a quadratic interpolation of these three points and took the stretching coefficient corresponding to the maximum of the interpolated curve. The error estimate was obtained from the expression derived by Weaver et al. (2011). The error was related to the maximum correlation coefficient, the size and the position of the window in the coda, the frequency bandwidth, and the inverse of the central frequency of the signal. We notice that in our context, the errors measured by the MWCS technique were generally larger than the errors from the ST. In the following, we only present the uncertainties that resulted from the MWCS technique, in order to keep values as conservative as possible.

**Damping Measurements**

The damping ratio of each mode can be computed by measuring the slope $\mu_r$ of the envelope of the IRFs band-pass filtered within the half-power bandwidth (Snieder and Şafak, 2006; Prieto et al., 2010; Sun et al., 2017). The damping ratio $\xi_r$ is given by

$$\xi_r = \frac{1}{N_0\omega_r} \sum_{i=1}^{N_0} |\mu_i|,$$

in which $N_0$ is the number of observations (typically the number of instrumented floors), and $\omega_r$ is the $r$th resonant frequency. Nakata and Snieder (2014) showed that with ambient vibration deconvolution interferometry, when noise sources are inside the building, the damping ratio measured by the amplitude decay of the deconvolution function is a combination of the intrinsic damping of the building and the radiation loss in the solid Earth at the base of the building. Here, we measure the damping separately on the acausal and causal sides of the IRFs, and our final estimation of the damping is the average of both sides.

**Results**

Figure 6 shows the 2159 IRFs (smoothed by a 6-hr moving window) for the north–south translational mode, measured on the roof with a source at the ground level. We can directly observe a temporal variation of the overall amplitudes of the IRFs, as well as time shifts of the phases within the later parts of the waveforms. The phase shifts will be analyzed through the velocity-variation measurements, whereas the amplitude variations will be interpreted as damping variations and/or ambient noise sources variations.
Velocity Variations

We measured the velocity variations in different lag-time windows along the waveforms and several frequency bands to assess the contribution of the propagation component versus the resonant component, as well as the contribution of the fundamental mode independent of the superposition of the overtones. In the following, we mainly analyze the north–south translational modes, which have higher signal-to-noise ratio (SNR). We focus on records deconvolved either from the ground floor or from the roof. The two methods (MWCS and ST) are also compared in the aforementioned contexts.

Figure 7a shows an example of $dv/v$ measured in the central part of the IRFs ($-3 < t < 3$ s) at each instrumented floor, for records deconvolved by the ground floor. The velocity variations are similar on each floor. This is certainly because the Green Building has not suffered strong damages, but one can expect this to change if damages are present. If this is the case, records of measurements pertaining to each floor can be used to account for the variations in floor stiffness (Sun et al., 2017). Therefore, a high-density seismic network is absolutely necessary to localize damage. On the other hand, in a low-seismic risk area where buildings are less likely to be strongly damaged, the similarity between the $dv/v$ on all floors shows that the number of sensors in a seismic array (e.g., to monitor the long-term aging of the structure) can be drastically reduced. Figure 8a,b shows a comparison of the $dv/v$ measurements performed with the MWCS and ST methods for the central part ($-3 < t < 3$ s) and the later parts ($15 < |t| < 24.5$ s) of the IRFs, respectively. The two methods behave similarly in both cases; however, the $dv/v$ signals differ depending on the analyzed lag times. The central part presents larger $dv/v$ variations ($\pm 1\%$), with a noticeable daily periodicity and uncertainties on the order of $0.5\%$. The later parts of the waveforms exhibit smaller $dv/v$ fluctuations ($\pm 0.5\%$), and the daily periodicity is weaker; the uncertainties fluctuate around $0.25\%$ in average. Certain periods present a strong scattering of the $dv/v$ measurements in the later part measurements, which correspond to departures of the ST measurements from the MWCS measurement in the central

Figure 6. Estimated IRFs of the Green Building for the north–south translational modes, filtered between 0.5 and 7.5 Hz. The vertical dashed lines indicate midnight and the vertical dotted lines indicate midday.

Figure 7. Velocity variations ($dv/v$) measured on the north–south translational modes IRFs. (a) $dv/v$ at each instrumented floor measured in the central part of the IRFs ($-3 < t < 3$ s) with the moving-window cross-spectral (MWCS) method, between 0.1 and 7.0 Hz. (b) Same as (a) but measured on the later part of the IRFs ($15 < |t| < 24.5$ s), between 0.5 and 1.0 Hz.
part. These periods correspond to times when the apparent damping is the strongest (Fig. 9) and, therefore, where the SNR is the poorest in the coda. From these observations, we can see that the ST is more sensitive to variations in the amplitudes of local ambient vibrations than in the MWCS technique. We also observe a longer term; there is a period of 8 days on both measurements. The $dv/v$ measurements performed on IRFs that were obtained by deconvolving by the roof (see Fig. 5) instead of the ground floor exhibit similar features (Fig. 10). For these IRFs, we take the central part as $(-3 < t < 3 \text{s})$ and the coda parts as $(0.5 < |t| < 3 \text{s})$. The IRFs computed with the virtual source on the roof are less sensitive to ground coupling (Snieder et al., 2006; Rahmani and Todorovska, 2013; Petrovic and Parolai, 2016; Taciroğlu et al., 2016). Therefore, the strong similarity between velocity-variation measurements that is shown between the roof virtual source IRFs and the ground-floor virtual source IRFs (Fig. 10) shows that the observed variations are due primarily to changes within the building. Moreover, according to the model of Rahmani and Todorovska (2013) and Snieder et al. (2006), the broadband pulses generated by the roof deconvolution should vanish due to a null reflection coefficient at the ground level. In the case of the Green Building, we observe that, although small, the reflection coefficient is nonzero (and may be negative), and a clear coda exists after the main pulse. The nature of the waves in this coda is not clear in the context of ambient vibration interferometry with internal sources of vibration. In the case of earthquake interferometry, however, Rahmani and Todorovska (2013) showed that the coda is made by the superposition of internal reflections and reflections at the base of the building (Fig. 5d). The coda carries the same velocity-variation information as the direct waves (Fig. 10).

Apparent Damping Variations

Figure 9a shows the time series of the damping variations measured on each instrumented floor. Again, the curves are extremely similar on each floor, presenting a local minimum almost every day during
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Figure 10. Velocity variations ($dv/v$) measured on the north–south translational modes IRFs for different windows along the waveforms (plain curves for the central parts, dashed curves for the coda parts) and different virtual sources, either the seventh floor deconvolved by the ground floor (thin curves) or the seventh floor deconvolved by the roof (thick curves).

As shown by Nakata and Snieder (2014), in theory, the amplitude decay of the waveforms depends on both intrinsic attenuation of the building and ground coupling and cannot be easily separated. The observed apparent damping variations are therefore difficult to relate to a simple cause and difficult to interpret. In our case, when the amplitudes of the ambient vibrations are too small, the amplitude of the deconvolution functions are strongly biased by the amplitudes of the deconvolved waveforms, and the damping measurements are thus unreliable. Above a certain level, however, when the SNR is high enough, the damping measurements seem to converge toward a constant value. We hypothesize that at low amplitudes, the nonpropagating noise dominates the raw signal, and the amplitude information of the IRFs is not reliable; when the amplitudes are larger, the propagating vibrations are larger than the noise and the IRFs amplitude information is more reliable. Because of this apparent nonlinearity, the correlation with weather parameters is difficult to estimate. The temperature, recorded on top of the Green Building, shows a slight link with the apparent damping (the two curves are anticorrelated at 55%; Fig. 11a–c). We also observe a 6 hour delay between the air humidity variations and the damping variations, but these estimations should be taken with caution. There is no significant correlation with the temperature (Fig. 11b–d).

Discussion

Link with the Modal Frequency Wandering

Tracking the wandering of the fundamental-mode frequency is a well-known technique that can be used to monitor the temporal variations of the stiffness of a building (e.g., Clinton et al., 2006; Nayeri et al., 2008; Mikael et al., 2013).

Here, we show that monitoring the velocity variations of the

Figure 11. Comparison between the measured amplitude decay (damping) of the north–south fundamental translational mode and two weather parameters. (a) Damping (dashed line) versus air humidity filtered between 6 and 400 hrs of period. (c) The cross correlation between the two curves shown in (a). Only the positive lag time is shown to focus on causality between the weather forcing and the observed damping. (b) Damping (dashed line) versus temperature filtered between 6 and 400 hrs of period. (d) The cross correlation between the two curves shown in (b).
The main assumption behind this concept is that any damage will modify the stiffness and/or energy dissipation of the building. Therefore, monitoring parameters sensitive to stiffness or attenuation, such as shear-wave velocity and damping of the normal modes of a building, should allow us to detect such damage. By comparing the dynamic response of the building between an intact state and a damaged state, we should be able to assess the extent of the damage and take action in terms of safety. However, defining an intact state is quite difficult because any structure responds to environmental forcing by reversibly changing its dynamic parameters. To detect damages as early as possible, we must be able to detect small damages and correct our dynamic parameter measurements for these changes that are not associated with damages.

Here, we show that the interferometric approach can be used to monitor continuously (and potentially in real time) the intact state dynamics of a building and the effects that environmental parameters, such as temperature and air humidity, can have on its shear-wavespeed propagation. Figure 13 shows the comparison and correlation between relative velocity measurements and air temperature and humidity time series. We display $dv/v$ measured on the central part of the downward- and upward-moving IRFs for the temperature and humidity, respectively, but measurements on the later parts of the IRFs show similar results. We show only the positive lag time of the cross correlation between the $dv/v$ and weather data because we are interested only in the causal actions of the weather onto the building. We observe a stronger correlation between $dv/v$ and humidity than between $dv/v$ and temperature. The humidity correlation is dominated by the longer period trend, whereas the temperature exhibits a stronger daily period correlation. It seems that the temperature is negatively correlated with the velocity variations, but we cannot rule out a positive correlation with a 12-hr delay. On the other hand, the positive correlation between the $dv/v$ and humidity is more robust and it seems that there is a 1 day delay between them. Time series longer than two weeks could help determine the correlations between the parameters with more accuracy. It is also possible that the relationship between the weather forcing and the velocity variations depends on the actual forcing period (the daily forcing having a different linear relationship from the weekly forcing). It might also be a nonlinear relationship, which would explain the small correlation coefficient between the temperature and the $dv/v$ measurements.

As stated by Mikael et al. (2013), the temperature effect on high-rise buildings does not exhibit a clear trend and may depend on each individual building itself. Some studies observe a positive correlation between stiffness and temperature (e.g., Clinton et al., 2006; Yuen and Kuok, 2010; Mikael et al., 2013), whereas others observe a negative correlation (Xia et al., 2012; Mikael et al., 2013) or even a mixed behavior (Mikael et al., 2013). In the case of the Green Building, the anticorrelation in phase is clear, but the correlation seems less robust when observing the amplitude.
As noted by Simon and Strong (1968), direct solar heating on the southern face of the building has a strong influence when compared to air temperature variations. We lack sufficient data on amounts of sunshine during the studied period, which would be necessary in order to be able to corroborate these observations.

The humidity influence on modal frequencies has been studied less, and most observations focused on the effects of heavy rainfall. Clinton et al. (2006) report an increase of the fundamental-mode frequency of the soil–structure system of the Millikan Library after heavy rainfall. This has been confirmed with modeling experiments by Todorovska and Al Rjoub (2006, 2009). However, they do not provide a comparison with the actual local air humidity. Results from Mikael et al. (2013), looking at rainfall, are inconclusive by lack of strong events. The variations observed at the Green Building are unlikely caused by heavy rainfall; only a small shower (10 mm) occurred on 19 May around 12 p.m. and was not followed by clear effects. Herak and Herak (2010) observed a high positive correlation between air humidity and frequency changes over a 19-month period; however, it is not clear if the correlation still holds on the daily or weekly period. In most cases, the humidity effect on the vibrational behavior of a building is believed to be caused by changes in the soil–structure coupling, as opposed to changes in the structure itself. The fact that we observe a strong correlation between the $dv/v$ measured on the downward-moving IRFs (which are supposedly not sensitive to the ground coupling) and the humidity might indicate that the wetting of the concrete plays a significant role in the observed stiffness changes. Because of its age, the structural concrete of the Green Building (directly exposed to the weather conditions) most likely exhibits an increased porosity, which in turn enhances its gas and water permeability by several orders of magnitude when compared with uncracked concrete (e.g., Wang et al., 1997). The diffusion rate of moisture in cracked concrete can reach several centimeters per hour (Wang et al., 1997; Kanematsu et al., 2009), enough to penetrate the entire thickness of the shear walls of the Green Building. Moisturizing the grain contacts induces a weakening of the concrete (e.g., Murphy et al., 1984; Van Den Abeele et al., 2002; Pimienta et al., 2014) that leads to a reduction of the shear wavespeed.

Can Nonlinear-Mode Interaction Be Used as a New Monitoring Tool?

A close inspection of the spectrogram presented in Figure 2 shows that the resonance peak around 6.6 Hz is actually made of at least three distinct peaks. They are observed clearly on the blowup in Figure 1Aa. Modal analysis applied on the upgoing IRFs (Sun et al., 2017) shows that these frequencies correspond to the fourth north–south translational mode; considering the three frequencies either together or separately, we observe the same mode shapes (Fig. 1A). This result lies in contradiction to the work of Trocha (2013), reported by Taciroglu et al. (2016), who found the third north–south translational mode at 8.25 Hz. This phenomenon is not visible on the east–west spectrograms, ruling out an imperfection in our horizontal components decoupling procedure.

Regardless of the exact nature of this mode, we observe a clear wandering of these frequencies. This wandering has a similar temporal fluctuation profile when compared to the wandering of the fundamental mode and the first overtone. It also exhibits the same relative variations with respect to the mean frequency (Fig. 15). The three frequency peaks present a parallel temporal behavior, which could suggest a bilinear behavior of the fourth north–south translational mode.
A single-degree-of-freedom bilinear system is characterized by two frequencies \( f_1 \) and \( f_3 \) which correspond to two different states of the system (e.g., with two different stiffnesses). These frequencies interact to give rise to a third frequency \( f_2 \), which is referred to as the bilinear frequency:

\[
f_2 = \frac{2f_1 f_3}{f_1 + f_3}
\]

(Chu and Shen, 1992).

Such behavior can be caused by the coupling of one translational mode with a torsional mode of nearby frequency (Boroschek and Mahin, 1991). In the case of the Green Building, however, modeling suggests that there is no torsional mode around 6.5 Hz. Bilinearity can also be observed in beams with breathing cracks where the two states of the system correspond to the open crack and the closed crack (e.g., Chu and Shen, 1992; Chondros et al., 2001; Yan et al., 2013; Bovsunovsky and Surace, 2015; and references therein). This model could suggest the presence of aging or fatigue cracks in the building. The fact that the splitting only affects the fourth translational mode would indicate that the cause of the bilinearity is well localized along the height of the building, potentially where floor drift is the largest.

Nonetheless, Figure 15 shows that the two strongest singlets (mode \( 4_1 = f_1 \) and mode \( 4_3 = f_3 \)) behave similarly to mode 1 and mode 2 but seem to lack their daily periodicity. Interestingly, the difference between \( f_1 \) and \( f_3 \) shows a stronger daily periodicity, while still retaining a fluctuation behavior that is similar to that of mode 1 and mode 2. This can be seen in Figure 16, where the cross correlation between the weather parameters and both the mode 4 wandering and the \( f_3 - f_1 \) fluctuations show results similar to \( dv/v \) measurements. The temporal variations of the nonlinear behavior of mode 4 could give new valuable information about temporal changes of some asymmetries or heterogeneities of the Green Building. Given the high frequency of the fourth mode, this nonlinear interaction would be sensitive, on first approximation, to heterogeneities on the order of the wavelength (50 m in this study). If confirmed, the study of high-frequency-mode nonlinear interaction would be useful not only for damage detection but also as a first step in damage localization due to their localized sensitivity. We believe that the first observations presented in this article can stimulate future studies in this direction.

**Conclusion**

We show with this study that deconvolution interferometry performed on continuous ambient vibrations can be used to monitor the structural dynamics of a building during normal conditions by computing empirical IRFs. By deconvolving the vibrations recorded inside the building by either the records on the ground floor or the records on the roof, we are able to repetitively measure the speed of the upward- or downward-moving shear-wave traveling inside the building and to track the temporal variations. The study of the exponential decay of the IRFs waveforms gives us access to the temporal changes of the building (and ground coupling) apparent damping, which is strongly biased by the amplitudes of the raw records. Our data processing and the velocity monitoring techniques used, which were fairly simple to implement, allowed us to obtain a temporal resolution of 6 hrs and an accuracy on the order of 0.1%–0.5%.

We show that measuring the seismic-velocity variations on IRFs filtered around a specific-mode frequency is equivalent to measuring the actual relative wandering of this modal frequency, a technique widely used to monitor buildings. Therefore, with the deconvolution interferometry technique, we provide an independent and potentially complementary way to perform building monitoring. We compared our \( dv/v \)
results with weather parameters and found a strong positive correlation with air humidity and a possible negative correlation with temperature. Longer time records would be necessary to clarify these relationships. Deconvolution interferometry can then be used as a powerful tool to study buildings’ dynamics under normal conditions. A better understanding of these natural and reversible variations would allow us to make corrections so that they are able to better detect structural damages.

Finally, we speculate that the fourth north–south translational mode of the Green Building is split due to a non-linear interaction in its structure. The temporal variations of the singlet difference seem to correlate with our $dv/v$ and frequency wandering observations, as well as with the weather data. If this observation is confirmed, we believe that it could provide a new tool in the efficient monitoring of buildings and potentially help locate damages.

Data and Resources

Seismograms used in this study were collected as part of a U.S. Geological Survey (USGS) experiment. Data can be obtained from Mehmet Çelebi (celebi@usgs.gov; last accessed May 2015).

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