Continuous Monitoring of HighRise Buildings Using Seismic Interferometry

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Front Matter

Title
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 the shear-wave velocity and the 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 vibration recorded by 36 accelerometers installed in the Green Building at the MIT campus to monitor the shear-wave speed and the apparent attenuation factor of the building. Due to the low strain of the ambient vibrations, we observe small speed changes followed by recoveries. We show 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 show that the air humidity is the factor dominating the velocity variations in the Green Building, as well as 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 by the amplitude of the raw vibrations and shows a more complex behavior with respect to the weather measurements. We have also detected normal mode non-linear interaction for the Green Building probably due to heterogeneity or anisotropy of its structure. We found that the temporal behavior of the frequency singlets may be used for monitoring.

Keywords: Building monitoring, ambient vibrations, deconvolution interferometry, relative seismic velocity changes, temporal variations, weather forcing, non-linearity.

Main text

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 receiver and retrieve the wave propagation between the two receivers only (e.g., Schuster, 2009; Snieder et al., 2006; Wapenaar and Fokkema, 2006). Seismic interferometry has been applied in several fields of seismology to image the subsurface at different scales with surface waves (Lin et al., 2008; Mordret et al., 2014, 2015; Picozzi et al., 2009; Shapiro et al., 2005) or with body waves (Draganov et al., 2009; Wapenaar et al., 2008). When used with ambient vibrations (the so called seismic noise), seismic interferometry 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 originally developed to monitor volcano pre-eruptive behavior (Anggono et al., 2012; Brenguier et al., 2008b; Mordret et al., 2010; Sens-Schönfelder and Wegler, 2006) and crustal effects of large earthquakes (Brenguier et al., 2008a, 2014; Froment et al., 2013; Minato et al., 2012; Wegler et al., 2009).

In civil engineering applications, seismic interferometry was first introduced as NIOM 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 of the Millikan Library in Pasadena, California. The technique has become very popular since then (e.g., Ebrahimian et al., 2014; Kohler et al., 2007; Rahmani et al., 2015; Todorovska, 2009; Todorovska and Trifunac, 2008a,b). The aforementioned studies use earthquake records as input excitation to determine the dynamic characteristics of the buildings. Due to the random and isolated occurrence of earthquakes, these signals are not well suited for continuous monitoring of civil structures (Nakata et al., 2013). The use of ambient vibrations, on the other hand, is more appropriate. Ambient vibrations can be recorded anywhere and at any time and have been used for building monitoring purpose through the measurement of the wandering of the modal frequencies (e.g., Clinton et al., 2006; Ditommaso et al., 2010; Mikael et al., 2013; Nayeri et al., 2008). These studies showed that this parameter is very sensitive to irreversible changes in the building structure, like defects and cracks caused by earthquakes. It is also sensitive to reversible variations like ambient temperature or humidity changes.

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 conclusion about the potential causes of the observed shear-wave velocity variations inside the building. In this paper, 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 and 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, MA), as well as its apparent-attenuation variations. These temporal changes are then correlated with different local weather parameters like the temperature and humidity to infer which one affects the most the building.

**Data and Methods**

We used 15 days of data (between May 12 and May 27, 2015) continuously recorded on 36 accelerometer channels deployed inside the Green Building.

The Green Building, currently the tallest building in Cambridge, was designed by I.M. Pei and constructed during the period of 1962–1964. 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., 19th and 20th floors). Heavy meteorological and radio equipments are asymmetrically mounted on the roof (Fig. 1(b)). Three elevator shafts are located on the eastern side of the building (Fig. 1(c)) and two stairwells are placed symmetrically at the NE and NW 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 running 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 characteristics can be found Čelebi 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 NS and EW translational vibration, the torsion, and the base rocking motion. The sensor locations and orientations are shown in Fig 1a. Note that the sensors are installed below the floor slabs. Fig 1c illustrates the sensor
locations at a typical floor. Because of these locations, the acceleration in each direction ($u_0$ for EW direction, $v_0$ for NS 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 y_1 \\
  v_1 &= v_0 + \theta_0 x_1 \\
  v_2 &= v_0 + \theta_0 x_2,
\end{align*}

where $u_1$ is the measured acceleration along the EW direction, $v_1$ and $v_2$ are the measured accelerations along the NS direction close to the eastern and western shear walls respectively, $x_1$, $x_2$ and $y_1$ are the sensor coordinates in the $x-O-y$ coordinate system with $O = (0, 0)$ shown in Fig 1c (see Table I in Sun et al. (2017) for the numerical values of the station coordinates). Therefore, the decoupled accelerations are:

\begin{align*}
  \theta_0 &= \frac{v_1 - v_2}{x_1 - x_2} \\
  u_0 &= u_1 + \theta_0 y_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 NS 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 $\sim2.55$ Hz, the second overtone at 5 Hz (Çelebi et al., 2014) and the third overtone around 6.6 Hz. Obvious is the daily pattern of the man-made ambient noise with higher amplitudes during working hours and smaller amplitudes during the nights. The two weekends
are also well observed (May 16-17 and May 23-25, with Memorial Day) with smaller noise amplitudes.

**Pre-processing 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 pre-processed to mitigate potential biases introduced by the non-stationarity of the recorded ambient vibrations. The raw data are high-pass filtered at 0.05 Hz, then, the amplitudes larger than 3 standard deviations of the 2 week-long record are replaced by the 3 standard deviation threshold value. Then, the two-week long records are chopped into 20 min long segments with 50% overlap and deconvolution interferometry is applied to each detrended segment such as:

\[
D_{U_n}(z, z_0, t) = \mathcal{F}^{-1}\left( \frac{U_n(z, \omega)U_n^*(z_0, \omega)}{|U_n(z_0, \omega)|^2 + \alpha \langle |U_n(z_0, \omega)|^2 \rangle} \right),
\]

where \(D_{U_n}(z, z_0, t)\) 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 \(z\), in which \(n\) is the index of the 20 min segment (\(n = 1 .. 2159\) in this study) and \(t\) the lag time. In the right-hand side of equation 7, \(\mathcal{F}^{-1}\) is the inverse Fourier transform, \(\omega\) is the angular frequency, * is the complex conjugate, \(\langle |U_n|^2 \rangle\) 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:

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

We tested different pre-processing 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 pre-processing approach affected only marginally our results, both for the velocity variation measurements and for the damping variation measurements. Figure 3 shows the central part of the estimated Impulse Response Functions (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), 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 on the type of vibration (the dashed-lines are for reference only, assuming a constant speed of $\sim 365$ m/s, $\sim 320$ m/s and $\sim 600$ m/s for the NS translational modes, EW 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. 4). We observe a clear symmetry between the negative and positive time-lags of the IRFs, both in phase and amplitude. While the phase symmetry is expected from the seismic interferometry theory, it should not be the case for the amplitudes because the attenuation always follows causality. The amplitudes should therefore increase with increasing negative time-lags (Snieder, 2007). The presence of ambient vibration sources inside the building may play the role of volumetric sources and balance the amplitudes at negative time-lags (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, Rahmani and Todorovska (2013); Snieder and Şafak (2006) showed that the deconvolution functions are the superposition of an acausal up-going wave with a causal down-going wave. The speed of these waves is the shear wave speed of the building (Fig. 5). We note a discrepancy between the velocity of the NS modes measured with the source on the ground floor
and the source on the roof. This could be due to dispersion or reflections caused by the internal structure of the building (Rahmani and Todorovska, 2013; Snieder and Şafak, 2006). 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; Snieder and Şafak, 2006) the up- and down-going 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 potential internal reflections in the EW direction (Fig. 5b). At higher frequency, a clear coda is following the main pulse and may be the consequence of multiple reflections at the base and inside the building (Fig. 5d) Rahmani and Todorovska, 2013).

**Velocity-variation measurements**

For monitoring applications the absolute value of the velocity does not need to be evaluated: only the relative velocity variations are needed. It is then possible to use techniques which are much more accurate that picking the absolute travel-times of seismic pulses propagating inside the building. The basic principle to measure relative seismic velocity variations ($dv/v$) is to compare a current waveform with a reference one by measuring their relative phase-shifts along the lag-time. Here, the current waveforms are the individual $D_{U_n}$ waveforms averaged in a 6 hours moving window (average of the nth deconvolution function with the 35 previous ones) and the reference one is $D_U$. We used two common techniques to measure $dv/v$ within the Green building: the Moving Window Cross-Spectral (MWCS) technique (Clarke et al., 2011), which is performed in the frequency domain and the stretching technique (Hadziioannou et al., 2009; Sens-Schönfelder and Wegler, 2006), 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: the propagating part at short lag times (-3 s \( \lesssim t \lesssim 3 \) s), where the fundamental mode and the overtones are superposed, and the resonant part at large lag times (-25 s \( \lesssim t \lesssim -6 \) s and 6 s \( \lesssim t \lesssim 25 \) s), where the fundamental mode dominates. We chose to analyze separately these two kinds of vibration. The MWCS technique is performed within the previously described time windows using small sliding windows with a length 6 times the central period of interest. The small windows move by 0.1 s. 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 signal 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 3 values: a time delay \( (t_{\text{delay}}, \text{in s}) \), an error for the time delay \( (errt_{\text{delay}}, \text{in s}) \) 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 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 \( errt_{\text{delay}} < 0.03 \) 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 the uncertainties of the relative velocity variations.

The stretching technique (ST) is based on the assumption that if a small velocity change occurs homogeneously in the medium, then the current waveform will simply be a stretched or compressed version of the reference waveform. The stretching coefficient is therefore the relative velocity variation \( dv/v \). 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 is stretched and then the current waveform is interpolated onto this new time axis. The correlation coefficient between the window of the stretched current waveform and the reference waveform is then computed and stored. The best $dv/v$ measurement is chosen as the stretching coefficient that maximizes the correlation coefficient between the current stretched and reference waveforms. To refine the estimation of $dv/v$ we use the maximum correlation coefficient and its nearest left and right neighbors. We perform a quadratic interpolation of these three points and take the stretching coefficient corresponding to the maximum of the interpolated curve. The error estimate is obtained from the expression derived by Weaver et al. (2011). The error is 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 are most of the time larger than the errors from the stretching technique. In the following, we only present the uncertainties are resulting from the MWCS technique to keep conservative values.

**Damping measurements**

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

$$\xi_r = \frac{1}{N_0 \omega_r} \sum_{i=1}^{N_0} |\mu_i|,$$  \hspace{1cm} (9)
where $N_0$ 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 hours moving window) for the NS 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 analysed 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 part from the resonant part and the contribution of the fundamental mode alone from the superposition of the overtones. In the following, we mainly analyze the NS translational modes, which have the higher signal-to-noise ratio and 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 ($-3 \text{s} < t < 3 \text{s}$) at each instrumented floor, for records deconvolved by the ground floor. The velocity variations
are similar at each floor. This is certainly because the Green building has not suffered strong
damages, but one might expect this to change if damages are present. If this is the case, records
at each floor can be used to invert for the variations of the floor stiffnesses (Sun et al., 2017) and
therefore, a high density seismic network is absolutely necessary to localize a damage. On the
other hand, in a low seismic risk area where buildings are less likely to be strongly damaged,
the similarity between the $dv/v$ at all floors shows that the number of sensors in a seismic
array (to monitor the long term ageing of the structure for example) can be drastically reduced.

Figure 8a) and b) show a comparison of the $dv/v$ measurements performed with the MWCS and
ST methods for the central part (-3 s < t < 3 s) and the later parts (15 s < $|t|$ < 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 time lags. The central part presents larger $dv/v$ variations (±
1%) with a noticeable daily periodicity and uncertainties on the order of 0.5%. The later part of
the waveforms exhibits smaller $dv/v$ fluctuations (± 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 late part measurements which correspond to departures of the
ST measurements from the MWCS measurement in the central part. These periods correspond
to times when the apparent damping is the strongest (Fig. 9) and, therefore, where the signal
to noise ratio is the poorest in the coda. From these observations we can see that the ST is
more sensitive to local ambient vibrations amplitudes variations than the MWCS technique. We
also observe a longer term ~8 days period on both measurements. The $dv/v$ measurements
performed on IRFs obtained by deconvolving by the roof (see Figure 5) instead of the ground
floor exhibit similar features (Figure 10). For these IRFs, we take the central part as (-1 s < t <
1 s) and the coda parts as (0.5 s < $|t|$ < 3 s). The IRFs computed with the virtual source on
the roof are less sensitive to the ground coupling (Petrovic and Parolai, 2016; Rahmani and
Todorovska, 2013; Snieder et al., 2006; Taciroglu et al., 2016) therefore, the strong similarity
between velocity variation measurements carried from the roof virtual source IRFs and ground
floor virtual source IRFs (Figure 10) shows that the observed variations are, at a first order, due
to changes within the building. Moreover, according to the model of Rahmani and Todorovska
(2013); Snieder et al. (2006), the broadband pulses generated by the roof deconvolution should
vanish due to a null reflection coefficient at the ground level. We observe in the case of the
Green Building that although small, the reflection coefficient is non-zero (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
(Figure 5d)). The coda carries the same velocity variation information as the direct waves
(Figure 10).

**Apparent damping variations**

Figure 9a) shows the time-series of the damping variations measured at each instrumented floor.
Again, the curves are extremely similar at each floor, presenting a local minimum almost every
day during morning hours and a maximum during the afternoon. This correlates strongly with
the amplitudes of the raw ambient vibrations (Figure 9b)) and might indicate that the measured
attenuation is biased and may only be apparent. Given equation 7, it is expected that some
amplitude information of the raw records is kept in the deconvolution functions. The non-
propagating ambient vibrations from sources inside the building are not corrected for by the
deconvolution of the ground floor records. However, the apparent damping presents a clear
non-linear relationship (Guéguen et al., 2016) with respect to the ambient vibration amplitude
(Figure 9c)): above a certain level of vibration, the apparent damping seems to stabilize around
5.5%.
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 unreliable. Above a certain level, however, when the SNR is high enough, the damping measurements seems to converge toward a constant value. We hypothesize that at low amplitude, the non-propagating noise dominates the raw signal and the amplitude information of the IRFs is not reliable whereas 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 non-linearity, 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 curve are anti-correlated at $\sim 55\%$, Figure 11a-b). We also observe a $\sim 6$ hours delay between the air humidity variations and the damping variations but these estimations should be taken cautiously. There is no significant correlation with the temperature (Figure 11c-d).

Discussion

Link with the modal frequency wandering

Tracking the wandering of the fundamental mode frequency is a well-known technique to monitor the temporal variations of the stiffness of a building (e.g. Clinton et al., 2006; Mikael et al., 2013; Nayeri et al., 2008). Here, we show that monitoring the velocity variations of the up-going IRFs filtered around the fundamental mode frequency is equivalent to measure the wandering of the fundamental mode frequency. For a simple 1D oscillator, the relative variation of frequency
\[ \frac{\Delta f}{f} = \frac{\Delta v}{v} - \frac{\Delta l}{l} \]  

(10)

where \( v \) is the shear-wave velocity of the building and \( l \) its length. If we assume that the length of the building does not change, we find that the relative frequency variations are equal to the relative velocity variations. In the ideal shear-beam case, the equality between velocity and frequency variations is also true for their absolute variations (Çelebi et al., 2016). This is clearly illustrated by Figure 12 where we see that the relative velocity variations, independently on the measurement technique, follow closely the wandering of the NS fundamental translational mode frequency. This interferometry-based technique is not limited to the fundamental modes but can be applied to overtones as long as their frequency can be easily isolated in the IRFs. In our example, we chose the simplest method to measure the frequency wandering, i.e. tracking the maximum of the fundamental resonance peak in the spectrogram shown in Fig. 2, between 0.5 and 1 Hz (Clinton et al., 2006). This technique is limited by the size of the signal sample used to compute the amplitude spectrum which gives a finite frequency resolution. Other more robust techniques, providing higher frequency resolution exist, such as the Random Decrement Technique (e.g., Mikael et al., 2013), but it was not necessary to use them here to illustrate our example. In any case, \( dv/v \) measurements from interferometry are as robust as modal frequency wandering observations and can provide independent information about the continuous dynamic behavior of a building.

**Influence of local weather parameters**

The main goal of structural health monitoring is to detect (and locate) any structural damage affecting a building through measurement of its dynamic behavior (Sohn, 2007). 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 a safety perspective. However, defining what an ‘intact state’ is quite difficult because any structure responds to environmental forcing by reversibly changing its dynamic parameters. In order to detect damages as early as possible, we must be able to detect small damages and therefore we must correct our dynamic parameters measurements for these changes which 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 environmental parameters, such as temperature and air humidity, can have on its shear-wave speed propagation. Figure 13 shows the comparison and correlation between relative velocity measurements and air temperature and humidity time series. We display \( \frac{dv}{v} \) measured on the central part of the down-going IRFs and up-going IRFs for the temperature and humidity, respectively, but measurements on the later parts of the IRFs show similar results. We show only the positive time-lag of the cross-correlation between the \( \frac{dv}{v} \) and weather data because we are only interested in the causal actions of the weather onto the building. We observe a stronger correlation between \( \frac{dv}{v} \) and humidity than between \( \frac{dv}{v} \) 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 hours delay. On the other hand, the positive correlation between the \( \frac{dv}{v} \) and the humidity is more robust and it seems that there is a 1 day delay between them. Time series longer than two weeks could help to 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 non-linear 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 building does not have a clear trend and may depend on the building itself. Some studies observe a positive correlation between stiffness and temperature (e.g. Clinton et al., 2006; Mikael et al., 2013; Yuen and Kuok, 2010) whereas others observe a negative correlation (Mikael et al., 2013; Xia et al., 2012) or even a mixed behavior (Mikael et al., 2013). In the case of the Green Building, the anti-correlation in phase is clear but the correlation in amplitude seems less robust. It can be noted, as observed by Simon and Strong (1968) that the direct solar heating on the southern face of the building has a strong influence compared to air temperature variations. We are lacking data of the amount of sunshine during the studied period to be able to corroborate these observations.

The humidity influence on modal frequencies has been less studied and most observations focused on the effects of heavy rainfalls. Clinton et al. (2006) report an increase of the fundamental mode frequency of the soil-structure system of the Millikan library after heavy rainfalls. 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 rainfalls, are inconclusive by lack of strong events. The variations observed at the Green Building are unlikely caused by heavy rainfalls: only a small shower ($\sim 10$ mm) occurred on May 19 around 12PM 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 months period, however, it is not clear if the correlation still holds
on the daily or weekly period. In most cases, the humidity effect on vibrational behavior of a building is interpreted to be caused by changes in the soil-structure coupling more than by changes in the structure itself. The fact that we observe a strong correlation between the $dv/v$ measured on the down-going 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 order of magnitude compared to un-cracked concrete (e.g., Wang et al., 1997). The diffusion rate of moisture in cracked concrete can reach several centimeters per hour (Kanematsu et al., 2009; Wang et al., 1997), enough to penetrate the entire thickness of the shear walls of the Green Building. The moisturizing of the grain contacts induces a weakening of the concrete (e.g., Murphy et al., 1984; Pimienta et al., 2014) that leads to a reduction of the shear-wave speed.

**Can non-linear 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 peaks. They are clearly observed on the blow-up in Figure 14a). Modal analysis applied on the up-going IRFs (Sun et al., 2017) shows that these frequencies correspond to the 4th NS translational mode: considering either the three frequencies altogether or separately, we observe the same mode shapes (Fig. 14b). This result is in contradiction with the work of Trocha (2013), reported by Taciroglu et al. (2016), who found the 3rd NS translational mode at 8.25 Hz. This phenomenon is not visible on the EW spectrograms, ruling out an imperfection in our horizontal components decoupling procedure.

Regardless the exact nature of this mode, we observe a clear wandering of these frequencies. This wandering has a similar temporal fluctuation profile than 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 4th NS 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 (with two different stiffnesses, for example). These frequencies interact to
give rise to a third frequency $f_2$ called bilinear frequency (Chu and Shen, 1992):

$$f_2 = \frac{2f_1f_3}{f_1 + f_3}. \tag{11}$$

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, how-
ever, 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. Bovsunovsky and Surace, 2015; Chondros et al., 2001;
Chu and Shen, 1992; Yan et al., 2013, and references therein). This model could suggest the
presence of ageing or fatigue cracks in the building. The fact that the splitting only affects the
4th 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. Interest-
ingly, the difference between $f_1$ and $f_3$ shows a stronger daily periodicity while still retaining
a similar fluctuation behavior as 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
non-linear behavior of Mode 4 could give new valuable informations about temporal changes
of some asymmetries or heterogeneities of the Green Building. Given the high frequency of
the 4th mode, this non-linear interaction would be sensitive, on first approximation, to hetero-
genieties on the order of the wavelength (∼50 m in this study). If confirmed, the study of high
frequency modes non-linear interaction would not only be useful 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 paper 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 con-
ditions’ by computing empirical IRFs. By deconvolving the vibrations recorded inside the
building either by the records at the ground floor or the records on the roof, we are able to repet-
itively measure the speed of the up- or down-going shear waves traveling inside the building and
to track their temporal variations. The study of the exponential decay of the IRFs waveforms
give 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, fairly simple to implement, allows us to obtain a temporal
resolution of 6 hours and an accuracy on the order of 0.1 to 0.5 %.

We show that measuring the seismic velocity variations on IRFs filtered around a specific
mode frequency is equivalent to measure 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 \( \frac{dv}{v} \) 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 correct for them to be able to better detect structural damages.

Finally, we speculate that the fourth NS translational mode of the Green Building is split due to non-linear interaction in its structure. The temporal variations of the singlet difference seem to correlate with our \( \frac{dv}{v} \) and frequency wandering observations as well as with the weather data. If this observable is confirmed, we believe that it could provide a new tool to efficiently monitor building and potentially help to locate damages.

Data and Resources

Seismograms used in this study were collected as part of an USGS experiment. Data can be obtained from Dr. Mehmet Çelebi (celebi@usgs.gov), last accessed 30 May 2015.

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