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Abstract: Dynamic non-classical nonlinear analyses show promise for improved damage diagnostics in materials that exhibit such structure at the mesoscale, such as concrete. In this study, nonlinear non-classical dynamic material behavior from standard vibration test data, using pristine and frost damaged cement mortar bar samples, is extracted and quantified. The procedure is robust and easy to apply. The results demonstrate that the extracted nonlinear non-classical parameters show expected sensitivity to internal damage and are more sensitive to changes owing to internal damage levels than standard linear vibration parameters.

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1. Introduction

Early damage detection is the mainstay for reliability analysis, service life prediction, and quality control of infrastructure materials such as concrete.[1] Test methods that are based on linear mechanical wave propagation and vibration show sensitivity to all types of distributed material damage. Well vetted standard test procedures that are based on linear mechanical wave measurements have been established.[2] Recently, more sophisticated mechanical wave propagation and vibration behavior responses have been employed to monitor subtle changes in material microstructure and early initiation of damage in concrete, through the deployment of diffuse wave modeling,[3] slow dynamics,[4] and nonlinear wave analyses.[5,6] The nonlinear analyses have been applied most broadly through a variety of Nonlinear Elastic Wave Spectroscopy (NEWS) techniques and the results show promise for detecting particular deterioration mechanisms such as thermal damage,[7] alkali-silica reactivity[8,9] or ageing of glass fiber reinforced cement[10] in concrete-like materials. However, NEWS techniques remain fairly difficult to carry out and analyze, and standard testing approaches have not yet been developed for concrete-like materials. Here, we introduce a robust approach to extract and quantify the full range of nonlinear material characteristics for damaged concrete using a standard resonance vibration testing set up.[11] Our experimental results qualitatively

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support a recent theoretical model, for the vibration of an elastic beam that contains a thin crack and nonlinear process zone ahead of the crack tip.[12] We demonstrate that our approach can be experimentally deployed and furthermore be applied and extended to material with distributed cracking.

In general, nonlinear materials whose elastic properties are dependent on their meso- and micro-structures, such as rocks, concrete, granular materials and sintered materials, fall in the category of nonlinear mesoscopic elastic materials (NMEM).[13] When an NMEM is mechanically excited it immediately exhibits nonlinear behavior at low strain amplitudes (fast dynamic effect), for example, measured Young's modulus decreases with increasing excitation amplitude. The fast dynamic effect is related to hysteresis in the strain-stress relationship, where friction and rough contacts between grains and microcracks give rise to the nonlinearity, thus providing a basis for sensitive damage detection.[14] In addition, a slow dynamic effect is also seen, wherein the original mechanical properties are eventually recovered with time after the external excitation is stopped after tens of minutes to hours.[14] Since these effects cannot be explained by classical theory of elasticity,[15] they are termed nonlinear non-classical (NN) effects.[16] A constitutive law that describes Young's modulus in terms of classical and NN behavior is given by[17]

$$E = E_o\lfloor 1 + \beta\varepsilon + \delta\varepsilon^2 + \cdots + \alpha(\Delta\varepsilon + \mathrm{sign}(\dot{\varepsilon}))\rfloor, \tag{1}$$

where E_o is the elastic Young's modulus, ε is the strain, β and δ are the nonlinear higher order strain parameters, α is a measure of material hysteresis, $\Delta\varepsilon$ is the strain amplitude, $\dot{\varepsilon}$ is the strain rate, and *sign* is the signum function. It is important to capture the full range of NN effects in order to fully characterize NMEM materials.[14]

2. Materials and methods

We demonstrate the approach using a set of three 40 mm × 40 mm × 160 mm water saturated portland cement mortar samples (denoted as A, B, and C) subjected to freezing-thawing cycles. The samples were produced following the guidelines of EN 196-1[18] with a portland cement CEM II/A-L 42.5R. The samples were cured in 20 °C water for 28 days after casting. Then they were subjected to freezing-thawing cycles that were achieved by reducing the temperature of the water saturated samples to −25 °C in a freezing chamber, maintaining that temperature for 24 h, and then thawing them in water at room temperature. As the internal pore water freezes, significant stresses are resolved within the material giving rise to distributed micro-cracking. Vibration tests configured to promote fundamental flexural vibration[11] were carried out after 0, 5, 10, 15, and 20 freezing-thawing cycles. An alumina ball (15 mm diameter) was dropped on the specimen and an accelerometer (0.956 mV/m/s^2) sensed the resulting surface motion. Signals of 8192 points per sample were recorded ten times with a digital oscilloscope using a sampling frequency of 50 kHz. Linear vibration parameters were derived using standard procedures.[11]

Unlike other proposed test methods for concrete, we extract the NN parameters using one signal obtained from a robust and standard testing configuration. The NN parameters were extracted using a short-time Fourier transform (STFT) based approach to track frequency changes during the signal ringdown test. Time-frequency dependence has been investigated in other dynamic systems using different approaches.[19–21] In this study, a sliding window moves through a single time response signal and transforms the time segment within the window to the frequency domain (amplitude spectrum) at every window position. The zero-padded windowed signal has a spectral line spacing of 0.5 Hz. The result depends on the preset window length, the over-lapping between succeeding windows and window type. The moving window analysis was stopped when the spectral amplitude reduced below a preset threshold value (th), here set to 1% of the maximum spectral amplitude. We used a Tukey window ($\alpha = 0.5$) with constant length of 128 sample points, which is equivalent to a

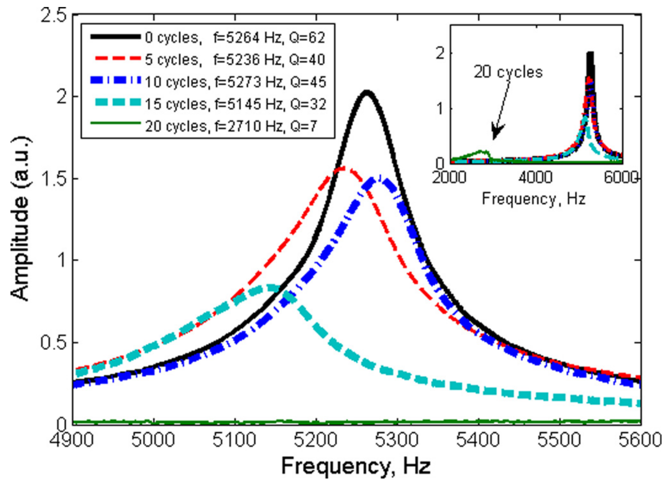

Fig. 1. (Color online) Resonance spectra after 0, 5, 10, 15, and 20 cycles of freezing and thawing of sample A.

window duration of 2.56 ms for our sampling conditions. This window length ensures that at least ten periods in the fundamental ringdown signal are captured. The window shift unit is 0.12 ms after transforming the time segment, which corresponds to a 95% level of overlap between consecutive windows.

3. Results and discussion

Figure 1 shows the standard vibration spectra for sample A, for all damage states. Frost damage affects the peak frequency and the quality factor (Q), or bandwidth, of the resonance. However the expected monotonic reduction in peak frequency and Q with increasing damage cycles is not seen at the early stages of damage, up to ten cycles. At later stages of damage, the samples show the expected drop in peak frequency and Q. Similar observations were made for samples B and C; these results are summarized in Table 1.

Figure 2 shows the NN features extracted from the vibration signal for early stages of damage: 0 cycle (top row), 10 cycles (middle row) and 15 cycles (bottom

Table 1. Dynamic properties of samples: flexural resonance frequency and quality factor Q. Mean of ten impacts and their standard deviation (SD) are shown.

Sample	Cycles	Frequency (Hz)	SD (Hz)	Q	SD
A	0	5263.5	0.5	61.8	0.8
A	5	5235.5	0.8	40.0	0.4
A	10	5272.8	2.8	45.4	1.3
A	15	5145.0	4.2	32.2	0.7
A	20	2710.1	90.9	6.5	0.6
B	0	5226.7	0.8	85.6	1.6
B	5	5157.0	1.8	39.1	0.7
B	10	5149.5	2.5	45.1	1.1
B	15	4941.3	8.0	23.8	0.7
B	20	2286.1	29.3	7.7	0.3
C	0	5203.5	1.4	55.1	7.0
C	5	5086.1	3.6	36.5	0.7
C	10	5118.4	1.9	39.0	0.5
C	15	4773.3	8.5	17.9	0.5
C	20	2550.1	27.2	9.8	0.6

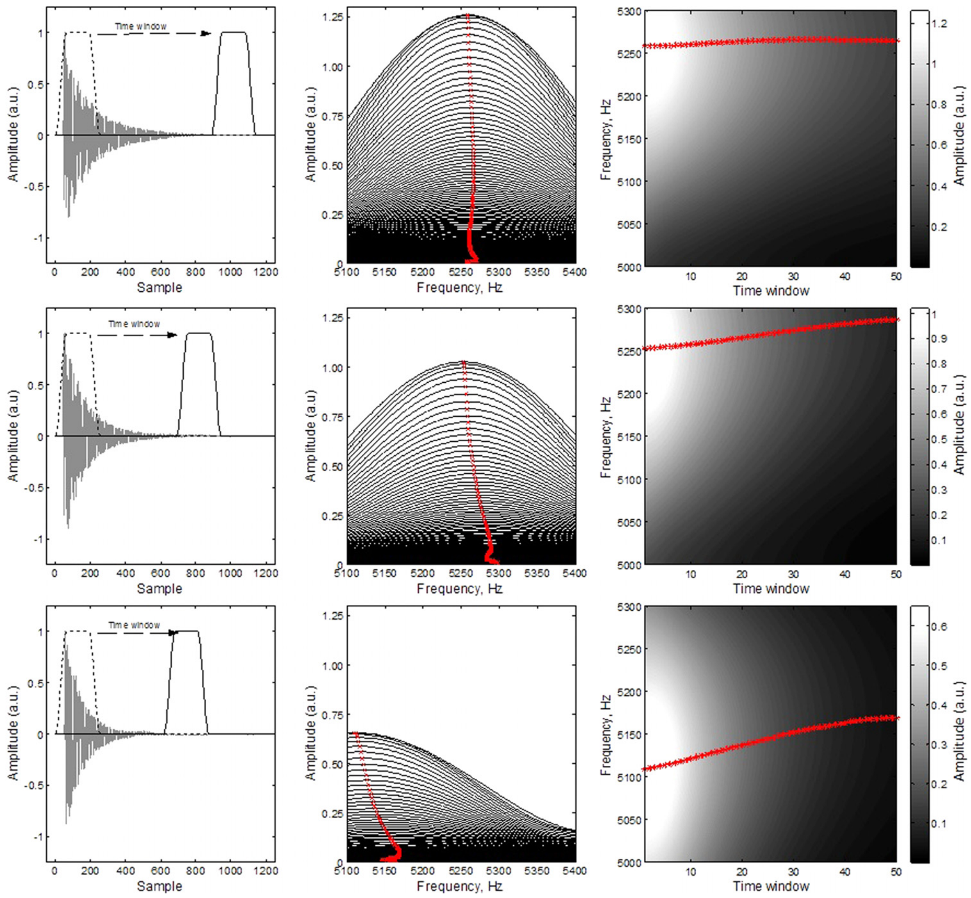

Fig. 2. (Color online) NN interpretation of standard vibration test data. Time signals (left column), extracted windowed spectra (center column) and stacked spectra plotted in gray scale as a function of window position in time (right column) for 0 cycle (top row), 10 cycles (middle row), and 15 cycles (bottom row) of freezing-thawing. Points indicating the peak amplitude positions form curves whose inclinations change with the number of freezing-thawing cycles.

row). The time signal shows the natural vibration amplitude ringdown with time and the final (stopped) window position is indicated (left column). The FFT spectra for all measured window positions (center column) and the interpolated time stacked spectra (right column) for different window positions are also shown. The plotted points indicate spectral maxima for every signal. In the absence of damage, the resonance frequency of a linear elastic material should be independent of amplitude. However, damaged concrete shows NN behavior, and thus, the resonance frequency is expected to increase as the amplitude decreases with time. The NN analyses show clear distinction between the early stages of damage that linear parameters fail to distinguish.

Three effects are observed with increasing damage: (1) the resonance frequency is reduced, (2) the quality factor Q is reduced, and (3) the NN effects increase. A dimensionless damage parameter D_F is defined to describe the reduction of modulus of elasticity with an increasing number of freezing-thawing cycles,

$$D_F = 1 - \left(\frac{fi}{fo}\right)^2, \qquad (2)$$

where fo is the initial "linear" resonant frequency and fi is the linear frequency after i freezing and thawing cycles, assuming that the Poisson's ratio and density are independent of

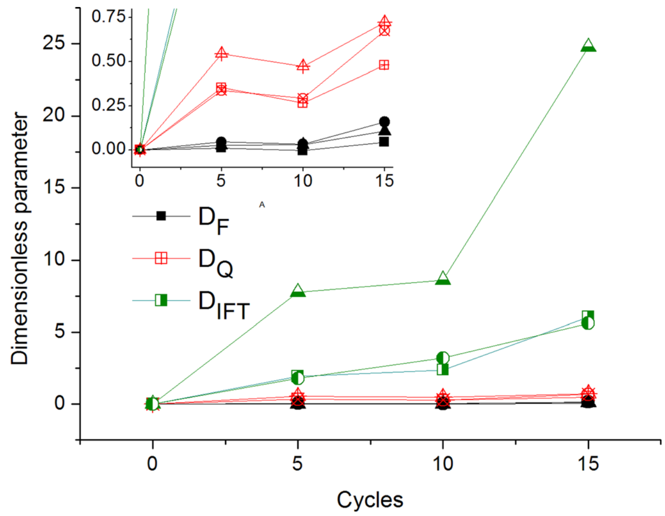

Fig. 3. (Color online) Evolution of dimensionless damage parameters with increasing number of freezing-thawing cycles for samples A (square), B (circle), and C (triangle). The inset shows the same curves plotted in an expanded vertical scale to magnify the variations of the damage parameters with cycle number.

the number of damage cycles. As a consequence of the increasing damage, the damping properties are changed and the signal becomes more attenuated. The dimensionless damage parameter (D_Q) obtained from the variation of the quality factor Q can be defined as the normalized variation of Q from the un-damaged state (Q_o) to the damaged state after i cycles (Q_i),

$$D_Q = \frac{|Q_i - Q_o|}{Q_o}. \quad (3)$$

Finally, to quantify the NN effect the cumulative frequency recovery with time, or integrated frequency time (IFT), is defined as

$$\mathrm{IFT} = \int_1^T \frac{f_{t=T} - f_{t=1}}{f_{t=1}} dt, \quad (4)$$

where the relative frequency variation from the frequency at the first time window ($f_{t=1}$) and those from the subsequent time windows ($f_{t=T}$), integrated over the time to a preset cut-off time window ($T = 50$). The NN damage parameter (D_{IFT}) is defined by

$$D_{\mathrm{IFT}} = \frac{|\mathrm{IFT}_i - \mathrm{IFT}_o|}{\mathrm{IFT}_o}, \quad (5)$$

where IFT_0 and IFT_i are IFT values after 0 and i cycles of freezing-thawing, respectively. In Fig. 3, the relative changes of resonance frequency, quality factor Q and NN effect are compared using the dimensionless damage parameters in Eqs. (2), (3), and (5). All three parameters start at a value of 0 for pristine samples and increase as damage is imparted. The results show that only D_{IFT} follows the expected monotonic increase with number of freezing and thawing cycles, and furthermore shows at least an order of magnitude greater sensitivity than those of D_Q and D_F.

4. Conclusion

We demonstrate that the full range of NN material behavior for NMEM can be extracted, in a straightforward and robust manner, using the proposed moving-window-analysis from information contained in one signal obtained from standard vibration tests. The extracted NN data show high sensitivity to internal distributed damage and complement linear material parameters extracted from the same signal.

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