Non-Contact control and damage diagnosis in concrete elements using Laser Scanning Vibrometry (LSV) method

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Outline of presentation

1. Concrete Non-Destructive Testing (NDT)
2. Non-Contact and Remote NDT
3. Laser Scanning Vibrometry (LSV) and NDT
4. Application of LSV for Concrete beam tensile crack diagnosis and damage state monitoring
5. Conclusions – Discussion
1. Concrete Non-Destructive Testing (NDT)

- **Non invasive** methods for the estimation of materials and construction physical and mechanical properties
- **Avoidance** of material sampling and specimens fabricating
- No need of laboratorial testing for material strength measuring
- Saving cost concerning specimens and material samples transportation, storage and conservation
- **In-Situ** estimation of mechanical and physical properties
- **Time efficient** and detailed inspection of a construction
- New technologies that adopt low cost sensors combined with portable and easy programmable electronics, allow the **installation of permanent** structural integrity monitoring systems (Smart Monitoring Grids)

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1. Concrete Non-Destructive Testing (NDT)

- Concrete control.
  - **Young Modulus Estimation**: Measurement of P-Waves (longitudinal) velocity (Ultrasonic method)
  - **Estimation of mechanical parameters – Structural Features**: (Young Modulus, Poisson Ratio, Local Stiffness, Damping etc.): Monitoring and acquisition of constructions’ response to impact excitation (Impact-Echo Methods, Dynamic Response monitoring)
  - **Compressive strength estimation**: Combination of Ultrasonic velocity measurement with empirical equations
  - **Crack depth estimation**: Exploiting surface wave propagation
1. Concrete Non-Destructive Testing (NDT)


• Construction dynamic response monitoring. Ordinarily in time domain – Signals Acquisition (Velocimeters, Accelerometers, Strain gauges etc.)

  Signal $j$-th value: $f_j, j=1:N$, $t_j=t_0+dt(j-1)$, Sampling frequency $FS=1/dt$

• Frequency Response Spectrum calculation – Fast Fourier Transform

$$F(\omega_k) = \frac{2}{FS} \sum_{j=1}^{N} f_j \exp(i \omega_k t_j), \quad \omega_k = \frac{2\pi}{Ndt} (k-1), \quad k = 1: N/2$$

• Dynamic features determination (Resonant frequencies and respective amplitudes, Eigenmodes etc.)

• Dynamic features are strongly physically correlated with structural and material properties (Stiffness, Damping-Mechanical Loss Factor and modal masses).
1. Concrete Non-Destructive Testing (NDT)

  - **If a damage occurs**, structural parameters will change and this change **will be imprinted at Frequency Response Spectra**.

![Frequency Response Spectrum](image)

- **Digital Oscilloscope – DAQ**
- **AMEL Teflon Piezoelectric sensor**
- **Impact point**
- **Artificial Damages**
- **Undamaged concrete member**

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2. Non-Contact and Remote NDT

- The majority of widespread NDT methods demand physical contact with monitoring structure
  - Preparation of construction surfaces (e.g. cleaning)
  - Sensors installation (e.g. Adhesive based attachment on constructions’ surfaces)
- Restricted access to monitoring structure's space
  - Bridges decks, Dam surfaces etc.
  - Concrete beams
- Access denied
  - Moving machine elements - High pressure and temperature operation
  - Monuments, Historical Constructions
  - Sculptures, Frescoes, Fine arts elements
3. Laser Scanning Vibrometry (LSV) and NDT

- Measuring the velocity of a vibrating construction’s point by exploiting the frequency shifting $\Delta f_r$, a Laser beam undergoes, due to Doppler effect.

\[ V = \frac{1}{2} \lambda \Delta f_r = \frac{1}{2} \lambda (f_{r_2} - f_{r_0}) \]

- Single Degree of Freedom Oscillator (Simulation of point dynamic response)
3. Laser Scanning Vibrometry (LSV) and NDT

- Surface **multi-point measuring** of constructional member vibration velocity – Data acquisition in time domain (Velocity Signals)
- Calculation of Fourier spectrum for each point of monitoring mesh
- Vibration modes mapping – Construction's dynamic features calculation

![Diagram of Laser Scanning Vibrometry](image)

Resonant Frequencies

Velocity Fourier spectrum on a specific scanning point

Mapping of dynamic response for each frequency point of scanning range

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- Portable laser head and processing unit.
- 1D vibration’s velocity measuring.
- Embedded data acquisition system.
- Bandwidth: 0 Hz-100 kHz.
- Max sampling frequency: 250 kHz.
- Max FFT points: 12800.
- Vibration amplitudes range: 1 mm/s – 10 m/s.
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- **Aims of experimental procedure**
  
  - Concrete dynamic response monitoring and damage diagnosis using LSV method
  - Scalar tensile failure
    - 3-point bending – Flexural test of concrete beam
    - 2 Loading-Unloading Cycles
    - Loading rate 0.5 (kN/s)
  - Steel fiber reinforced concrete
    - C20/25, 3 months age
    - Bending Length, 450 mm
    - Beam dims: 750x150x90 mm
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Aims of experimental procedure

- Examined Damage States
  - **Undamaged State**: Intact beam
  - **Damage State 1**: Initial tensile crack (Approx. at 12-15 kN) 1\(^{\text{st}}\) Loading Cycle
  - **Damage State 2**: Total collapse of concrete* (Approx. at 4-6 kN) 2\(^{\text{nd}}\) Loading Cycle

* Beam macro-geometric continuity is retained only due to steel fiber activation

- [Intact Beam Image]
- [Tensile Crack Image]
- [Damage State 2 Image]
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- Experimental set-up and procedure

![Experimental set-up and procedure diagram](image)
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- 125 scanning points, monitoring mesh
- Mechanical Vibration Actuator – Shaker LDS-V101 (Bruel & Kjaer)
- Frequency Generator. Harmonic excitation at 150, 200, 300, 350, 500 and 600 (Hz). **Perpendicular to bending plane direction.**
- Velocity signal Acquiring $F_S=3125$ (Hz)
- Number of FFT points: 800
- Range of Fourier Frequencies 100-1550 (Hz)
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- Vibration mapping: 2D polynomial regression of spectral velocity
- Efficient illustration of vibration modes using a relative small number of scanning points
- Estimation of vibration velocity distribution on non-scanned areas (technical restrictions)

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Scanning Results

- Spectral velocity distribution after polynomial regression for excitation frequencies 150 and 200 Hz.
- No significant changes of vibrations patterns among the different damage states.

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- **Scanning Results**
  - Spectral velocity distribution after polynomial regression for excitation frequency 300 Hz.
  - Detectable changes of vibrations patterns among the different damage states.
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- **Scanning Results**
  - Spectral velocity distribution after polynomial regression for excitation frequency 500 Hz.
  - **Significant changes of vibrations patterns among the different damage states**

![Velocity response colormap at 500Hz for fr_exo = 500Hz](image)

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Scanning Results

- Spectral velocity distribution after polynomial regression for excitation frequency 600 Hz.
- Significant changes of vibrations patterns among the different damage states

![Velocity response colormap at 600Hz for fr_{exo}=600Hz](image)

![Average spectrum for all scanning points - 600 Hz excitation](image)
5. Conclusions – Discussion

- **Laser Scanning Vibrometry** based measurement of vibration velocity, exploiting the Doppler effect a Laser beam undergoes, can be manipulated for the establishment of a Dynamic Motion based Non-Destructive Method for the **non-contact** and **remote** monitoring of concrete structures.

- Laser Scanning Vibrometry (LSV) **allows multipoint measuring of constructions’ dynamic response**, contributing to the structural members vibration mode mapping (Surficial Experimental Modal Analysis).
5. Conclusions – Discussion

- Application of LSV method
  - Monitoring of vibration patterns among different damage states
  - Detection of changes in concrete dynamic response because of damage generation
  - Localization of damage position

- Proposed methodology can also implemented for the dynamic monitoring and damage diagnosis of several brittle/rock materials built constructions like masonries, sculptures, frescoes, Mosaics and historical buildings from stones (e.g. temples)
5. Conclusions – Discussion

- AMEL Current Research Activity on LSV based NDT
  - Damage mapping in concrete layered walls
5. Conclusions – Discussion

- AMEL Current Research Activity on LSV based NDT
  - Damage diagnosis in historic masonries
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