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Integrating Modal Analysis and Seismic Interferometry for full structural dynamic response: Giotto's Bell Tower.

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Ambient Vibration Test

Ambient Vibration Test is commonly used to identify the dynamic response of the Building.

Classic Method Operational Modal Analysis:

- OMA is passive seismic tool for Structural frequencies, Modal shapes and Damping identification. We applied the Enhanced Frequency Domain Decomposition (EFDD)
  - Calibrate Numerical Model
  - Structural Health Monitoring (SHM) purposes.

Seismic Interferometry is performed on the same seismic data:

- IRFs (Impulsive Response Function) allow to estimate seismic wave velocity (V_s and V_p).
  - V_s a new parameter for SHM (Velocity is less affected by SSI than frequency).
  - Seismic Wave analysis integrated with the structural frequencies gives information on Structure Soil Interaction.

Dynamic Monitoring

10 Seismic Stations equipped:

- Broadband 3-component seismometers (Lennartz 5s, Guralp 10s, Guralp30s)
- Digitizer 24 bit (Guralp, CMG-DM24) sampling at 100Hz
- Synchronization using GPS

36 hours seismic survey

Automatic Identification Modal Parameters – *EFDD*

Assumption --> Modal Shapes are stationary for 3 hours

$$C(u_1^{t_o}(\omega_1), u_1^{t_o+n\Delta t}(\omega_1)) = \frac{|[u_1^{t_o}(\omega_1)][u_1^{t_o+n\Delta t}(\omega_1)]^H|^2}{([u_1^{t_o}(\omega_1)][u_1^{t_o}(\omega_1)])([u_1^{t_o+n\Delta t}(\omega_1)][u_1^{t_o+n\Delta t}(\omega_1)])}$$

MODAL

Rainieri & Fabrocino, 2010

Lacanna et al, 2016

COHERENCE

First singular values

6 Modal Frequencies Identified

Figure 3

First and Second Modal Shapes

1° Longitudinal - 0.623 Hz

2° Transversal - 0.647 Hz

1°+2° Shapes Mode

1° and 2° Shapes Mode moves together along the diagonal of the square plan of Giotto's Bell Tower

The two first Shapes Mode are coupled and resulting in circular movement slightly eccentric in North-South direction

III° -IV° -V °- VI° Modal Shapes

III° – 2.543 Hz

IV° – 3.081 Hz

V° – 3.156 Hz

VI° – 5.731 Hz

4° and 5° Shapes Mode as the first two modes moves approximately to the diagonal of the square plan of Giotto's Bell Tower

Automatic Tracking of Modal frequencies

The Modal frequencies are detected automatically for 36 hours and compared with temperature

Frequency (Hz) Mean	Frequency (Hz) Min (%)	Frequency (Hz) Max (%)
0.623	0.618 (0.76)	0.628 (0.80)
0.647	0.642 (0.81)	0.652 (0.73)
2.543	2.520 (0.90)	2.573 (1.18)
3.081	3.052 (0.93)	3.105 (0.79)
3.156	3.134 (0.68)	3.174 (0.57)

A positive correlation is found
between the 6 modal frequencies
and temperature.

Frequency changes ≤ 1.1 %

Flexible structure

The building horizontal displacement is a sum of three terms

$$\frac{1}{f_0^2} \cong \frac{1}{f_H^2} + \frac{1}{f_R^2} + \frac{1}{f_{fixed}^2}$$

Translation   Rotation   Deformation
Soil foundation   of Building

$$\frac{1}{f_0^2} \cong \frac{1}{f_R^2} + \frac{1}{f_{fixed}^2}$$

$$f_H \rightarrow \infty$$

$$f_R = \sqrt{\frac{K_\phi}{I_x}}$$

The modal frequencies extracted with OMA (f_0) is related to the mechanical properties of the building but is also affected by the soil-structure interaction

For Flexible structure f_{fixed} is given by basic equation: $f_{fixed} = 0.560 \cdot \frac{r_i}{h^2} \sqrt{\frac{E}{\rho}}$

$r_i = 4.26$ m Inertia radius cross-section

$h = 84$ m Elevation of the building

$$\sqrt{\frac{E}{\rho}}$$

Compressional P-wave velocity

**the seismic velocity
is estimated by interferometry**

Seismic Interferometry

Evaluates the IRFs through the deconvolution of the signals:

$$D(\omega) = \frac{u_i(\omega)u_{ref}^*(\omega)}{|u_{ref}(\omega)|^2 + \varepsilon}$$

$u_{ref} \rightarrow$ Station locate to the Top

*Sneider & Safak,
BSSA 2006*

$$f_{fixed} = 0.560 \cdot \frac{r_i}{h^2} \sqrt{\frac{E}{\rho}} = 0.70 \text{ Hz}$$

Rocking Frequency

$$\frac{1}{f_0^2} \cong \frac{1}{f_R^2} + \frac{1}{f_{fixed}^2}$$

$$f_0 = 0.623 \text{ Hz} \quad \text{OMA technique}$$

$$f_{fixed} = 0.70 \text{ Hz} \quad \begin{array}{l} \text{Interferometry} \\ \text{Geometrical properties} \end{array}$$

ROCKING FREQUENCY:

$$f_R = 1.36 \text{ Hz}$$

Rocking Stiffness

$$\tilde{K}_r = 2278 \text{ GN} \cdot \text{m} / \text{rad}$$

The soil structure interaction reduces the fixed-base frequency by 8% and it is expected by considering the high $V_s=380 \text{ m/s}$ of the soil foundation

Results

Automatic identification EFDD technique on Giotto' Bell Tower:

- Identifies **6 main frequencies and associated modal shapes**
- The 1° - 2° modes move to **the diagonal of the square plan** $f_0 = 0.623 \text{ Hz}$

Seismic Interferometry technique on Giotto' Bell Tower:

- Seismic velocity $V_p=2040 \text{ m/s} \rightarrow$ **Fixed base frequency** $f_{fixed} = 0.70 \text{ Hz}$

$$\frac{1}{f_0^2} \cong \frac{1}{f_R^2} + \frac{1}{f_{fixed}^2}$$

Conclusions

Integrating results of the two techniques

$$f_R = 1.36 \text{ Hz}$$

- Provides detail information on the degree of soil-structure interaction.
- The rocking frequency is consistent with the geotechnical properties and it reduces the fixed base frequency of 10%
- The value $f_R=1.36 \text{ Hz}$ can be used to validate analytical relationship to compute the rocking stiffness for advanced seismic analysis

The full structural dynamic identification (OMA- Interferometry) shows a Weak contribution of soil-structure interaction