COMMISSION OF THE EUROPEAN COMMUNITIES
FP7- INFRASTRUCTURES-2008-1
SP4-Capacities

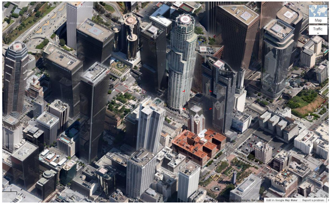
SERIES
SEISMIC ENGINEERING RESEARCH INFRASTRUCTURES FOR EUROPEAN SYNERGIES

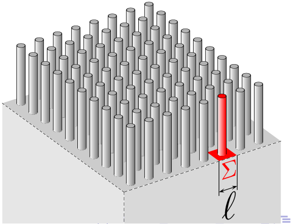
FINAL WORKSHOP - *Ispra (IT), May 30th, 2013*

Multi-Building Interactions and Site-City Effect

- an idealized experimental model -

L.Schwan (PhD student), C.Boutin, M.Dietz, L.A.Padron, P.-Y.Bard, S.Castellaro, E.Ibraim, O.Maeso, J.J.Aznárez and C.Taylor

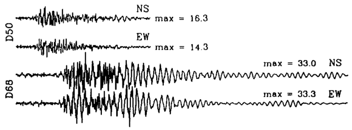




A Site-City effect ?

Context

- Structure-Soil-Structure Interactions not taken into account in usual engineering practice
- Records in urban area during Mexico earthquakes : long duration, beatings. Might they depend on the city ?
  (Wirgin & Bard, 1996, BSSA)
- Assumptions ? Methods ?



Horizontal accelerations recorded in Mexico on firm ground (top) and in the lake bed zone (bottom) during the 25th April 1989 event [Chavez-Garcia et al., 1994]

Objective

To identify, describe and quantify large scale multiple interactions phenomena through experimental, numerical and theoretical crossed analyses

Interdisciplinary collaboration to approach the issue

Team members **Institute**	**Numerical Modelling**	**Theoretical Modelling**	**In-Situ Data**
Pr. P.Y. Bard (lead user) ISTerre, University of Grenoble CNRS/IRD/IFSTTAR - France	Spectral Element Simulation		Structures and ground motion
Pr. C. Boutin, PhD student L. Schwan ENTPE, University of Lyon LGCB/CNRS - France		Homogenization of periodic systems	
Dr. L.A. Padròn, J.J. Aznàrez & O. Maeso University of Las Palmas de Gran Canaria - Spain	Boundary/Finite Element Methods		
Pr. S. Castellaro University of Bologna - Italy	Reverse analysis		Structures and ground motion

and from the host facility *EQUALS* :
M. Dietz, E. Ibraim, C. Taylor, *University of Bristol - U.K.*

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Outline

Theoretical model : city impedance analysis

Design, shaking and instrumentation

Experimental results / city impedance analysis

Numerical simulations / city impedance analysis

L.A. Padròn, J.J. Aznàrez & O. Maeso

Conclusions

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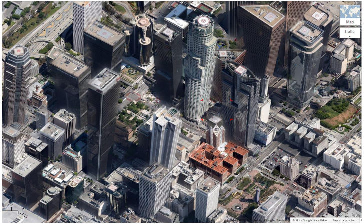
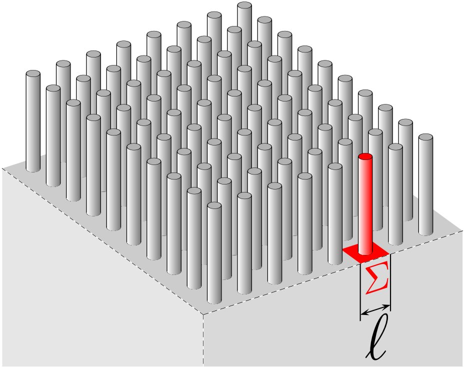
Conclusions

Idealization of a city

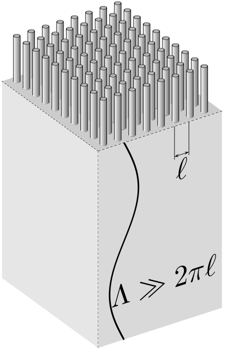


Los Angeles - downtown



Σ-periodic distribution of identical resonant structures

Periodic surface under long wavelength



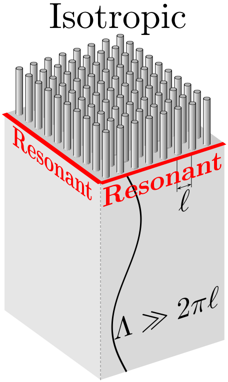
- Σ-periodic surface

$$\Sigma = \ell^2$$

- Scale separation : the wavelength is much larger than the width of the period

$$\Lambda \gg 2\pi\ell$$

Periodic surface under long wavelength



- Σ-periodic surface

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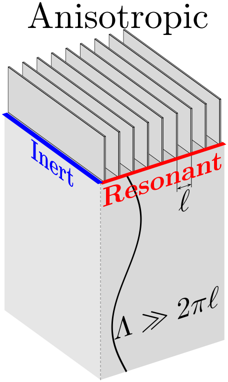
- Isotropic :

Same resonant behaviour in **all** directions

Periodic surface under long wavelength



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- Anisotropic :

Resonant direction & **Inert direction**

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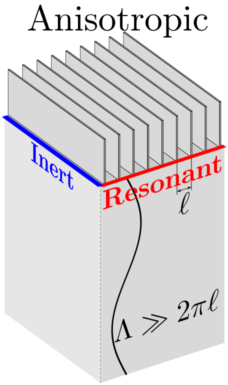

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Resonant direction $\&$ Inert direction

- Constructive interferences

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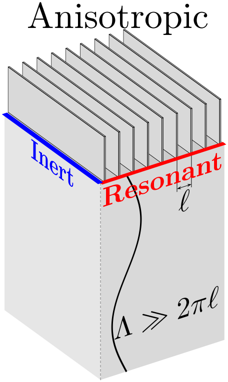

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Surface stress= **Force exerted by Resonator**$/|\Sigma|$

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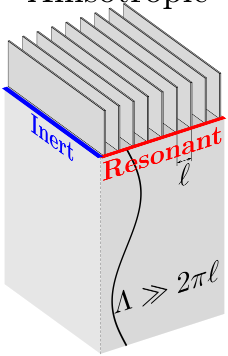

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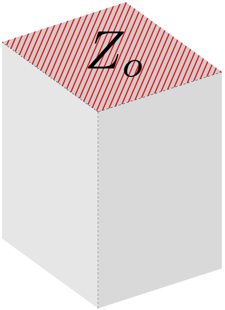
Surface stress= **Force exerted by Resonator**$/|\Sigma|$

- Resonator exerts a force on surface because it is shaken

Resonator Force = Resonator Impedance $\mathcal{Z}$ $\times$ Surface velocity

Periodic surface under long wavelength

City Impedance



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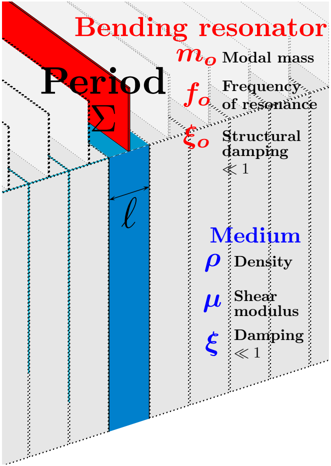
- City impedance $Z_o = \mathcal{Z}/|\Sigma|$

Surface stress = City impedance Z_o $\times$ Surface velocity

City impedance



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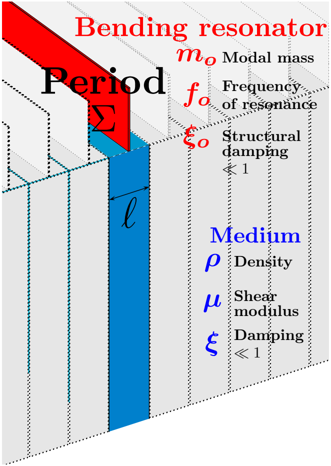

Ratio city impedance Z_o / soil impedance Z_S :

- parameter η
- resonator-dependent dynamical function

$$\frac{Z_o}{Z_S} = \boldsymbol{\eta} \, \frac{i\frac{f}{f_o} + 2\xi_o \frac{f^2}{f_o^2}}{1 - i2\xi_o \frac{f}{f_o} - \frac{f^2}{f_o^2}}$$

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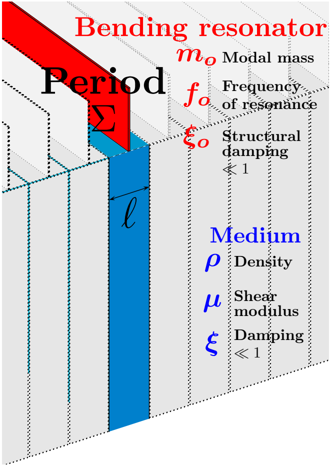

Interaction parameter

$$\eta = \frac{m_o\, 2\pi f_o}{|\Sigma|\sqrt{\rho\mu}}$$

e.g. Mexico : $\eta \sim 10\%$

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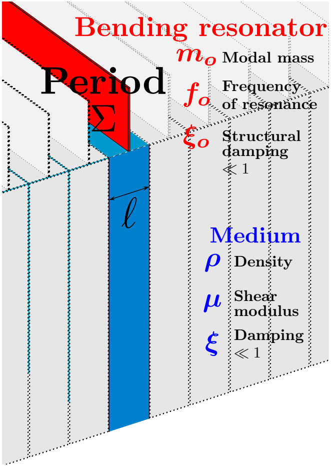

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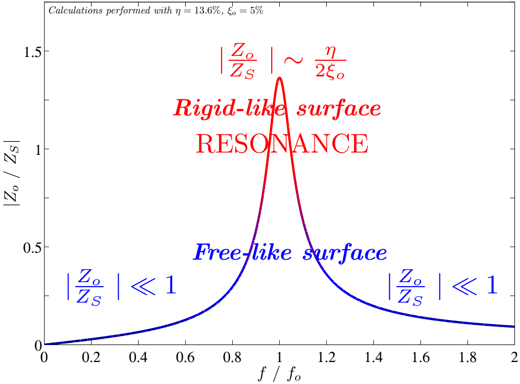
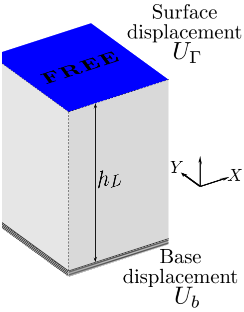
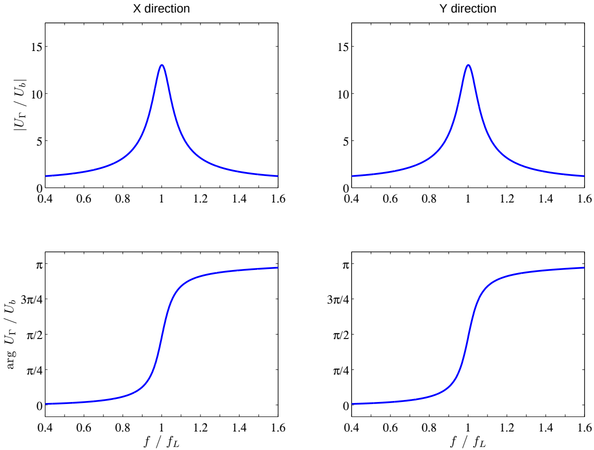


City resonance coincidences with layer resonance

The layer would like to amplify the displacement imposed at its base





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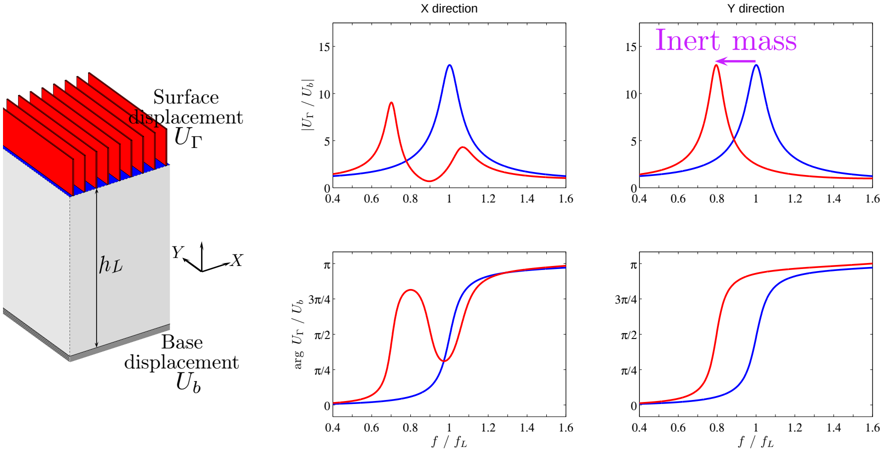

BUT the resonant surface imposes

- a free-like condition in Y inert direction
- a rigid-like condition at resonance in X direction

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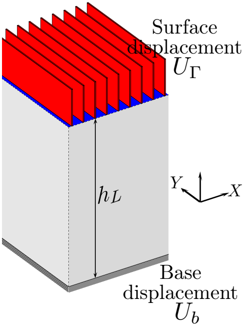

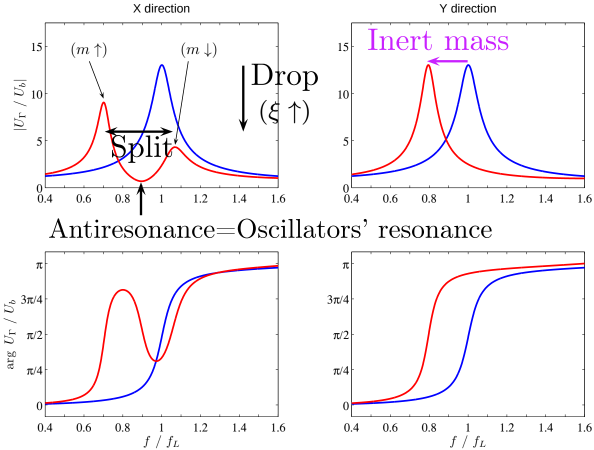

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Outline

Design

Layer

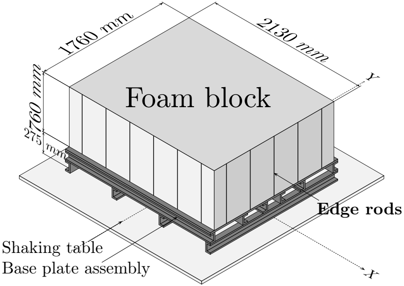
City

Design

Layer

City

- Elastic, linear, isotropic
- Eigenfrequency $f_L < 15\ Hz$
- Aspect ratios > 2



- $h_L = 76\ cm$
- $f_L = 9.36\ Hz$ in X ($9.11\ Hz$ in Y)
- $\xi = 4.9\ \%$

Design

Layer

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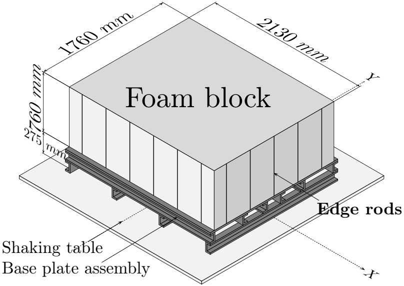

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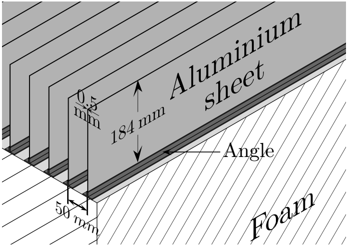
- $f_L = 9.36\ Hz$ in X ($9.11\ Hz$ in Y)
- $\xi = 4.9\ \%$

City

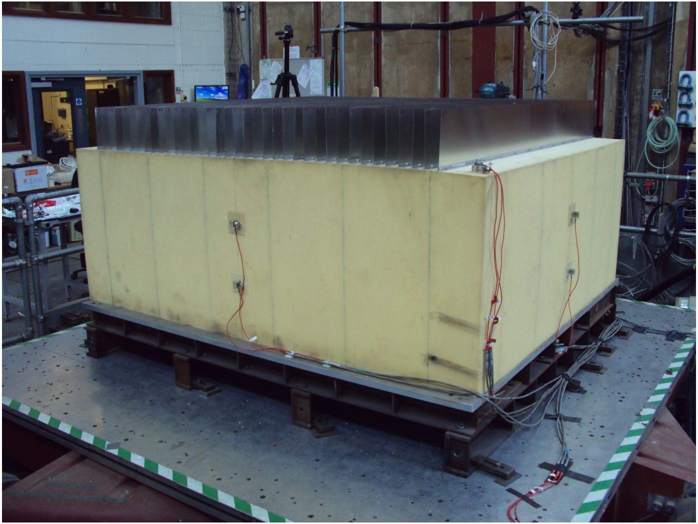
- Period width $\ell \ll \Lambda$ Wavelength
- Eigenfrequency $f_o \approx f_L$
- Modal mass $m_o \sim$ Mass of layer under period



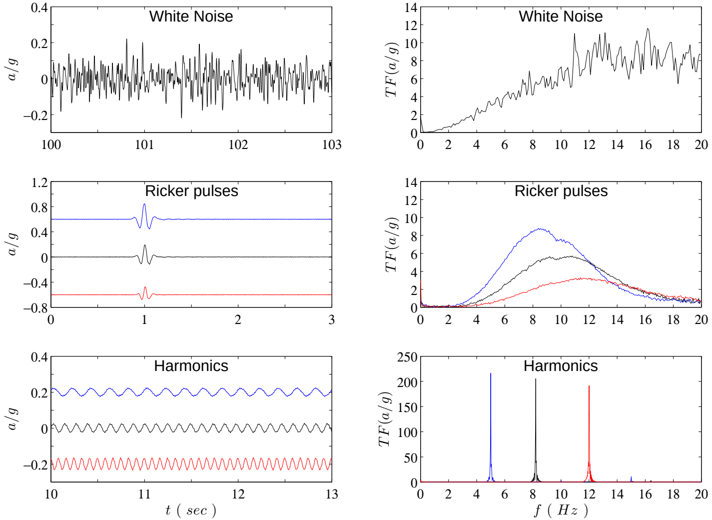
- Period width $\ell = 5\ cm$
- $f_o \approx 8.4\ Hz \quad \xi_o \approx 5\ \%$
- $\eta \approx 13.6\%$ (*Mexico* : $\eta \sim 10\%$)

Mock-up

Period $\ell = 5\ cm$ 37 resonators

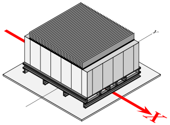


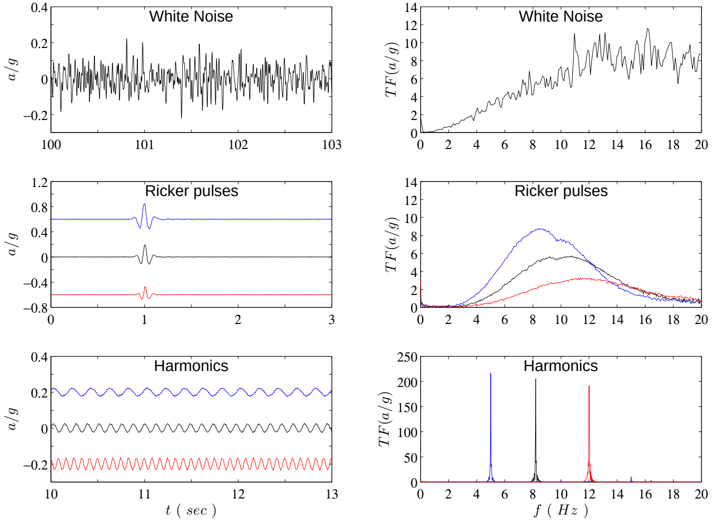
Shakings



Shakings

in X
resonant direction





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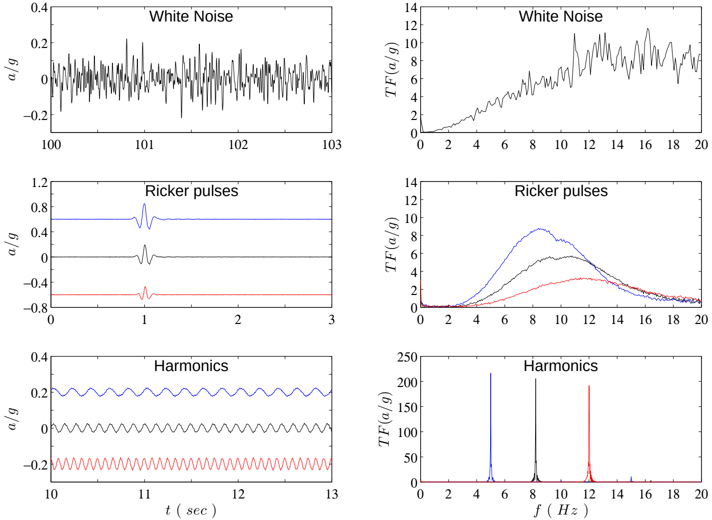
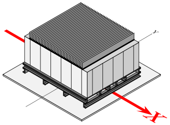


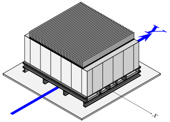
in X

resonant direction



in Y

inert direction



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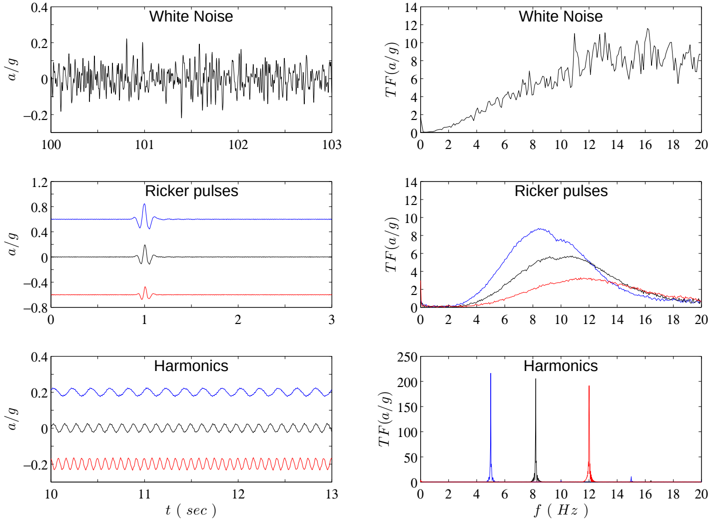
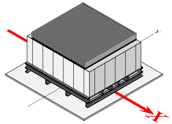


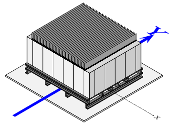
in X

resonant direction



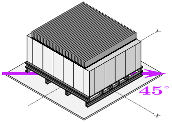
in Y

inert direction



at 45°

superposition of X and Y



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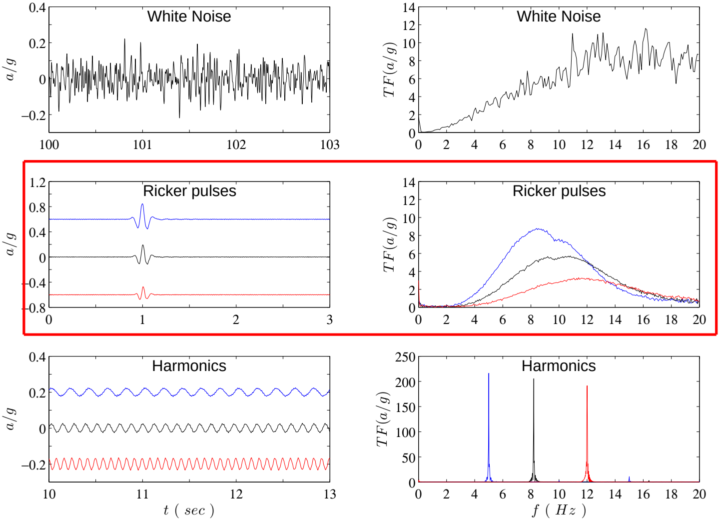
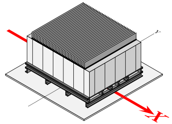


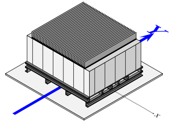
in X

resonant direction



in Y

inert direction



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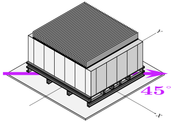
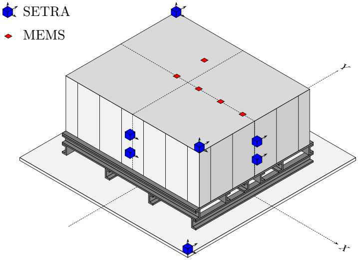
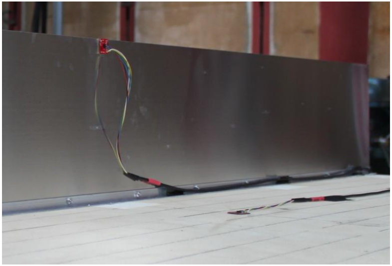
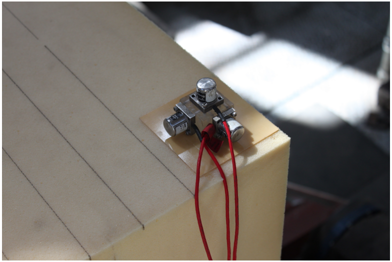


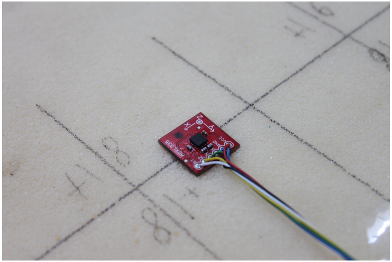
Instrumentation







SETRA : 1D, 30 grams each, $8\ cm$-wide base plate

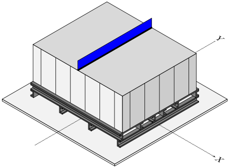


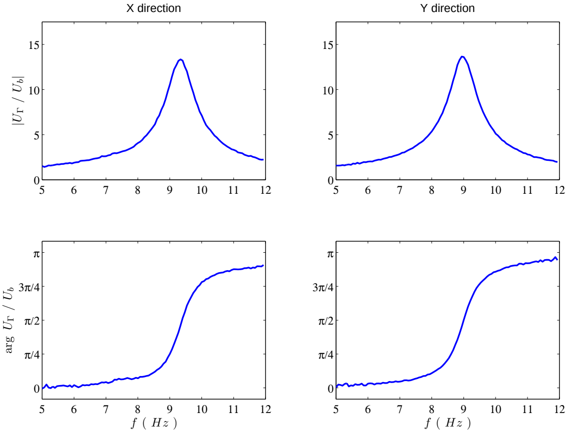
MEMS : 3D, 2 grams, $2\ cm$ wide

Outline

Drastic changes in spectrum Surface/Table

1 sheet



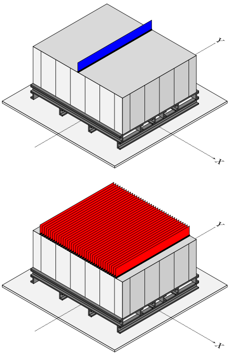


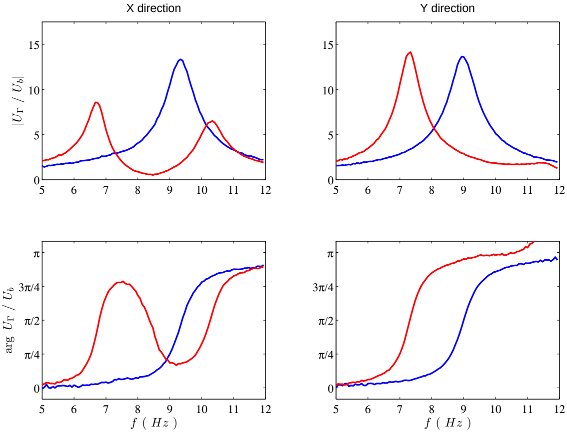
- 1 resonator : usual layer's resonance

Drastic changes in spectrum Surface/Table

1 sheet

37 sheets



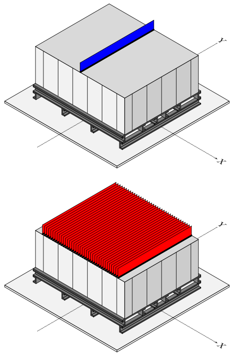


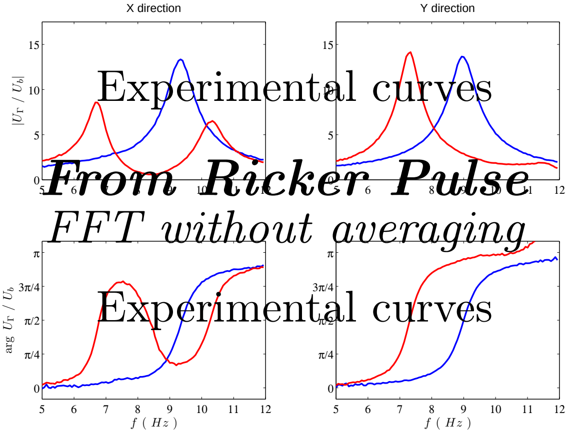
- 1 resonator : usual layer's resonance
- 37 resonators : in X resonant direction : drastic change in layer's resonance
- 37 resonators : in Y inert direction : usual resonance peak

Drastic changes in spectrum Surface/Table

1 sheet

37 sheets





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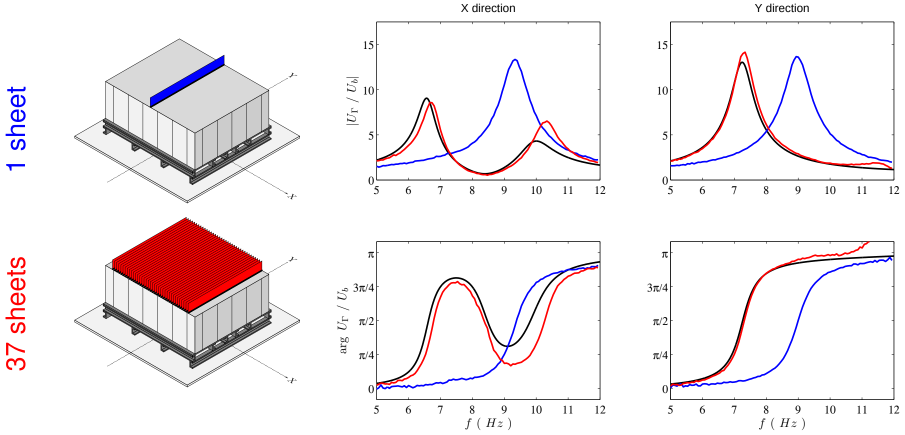
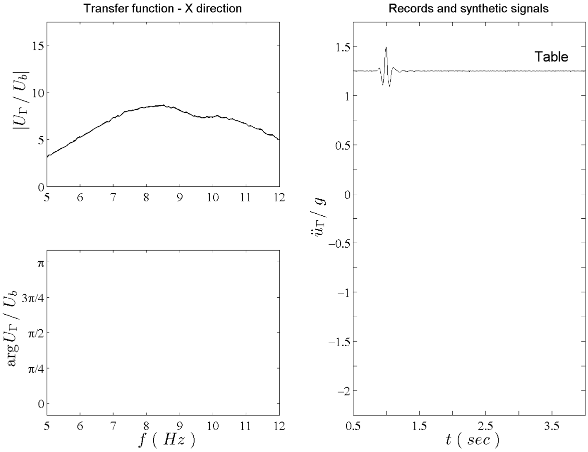
- 37 resonators : in Y inert direction : usual resonance peak

Drastic changes in spectrum Surface/Table



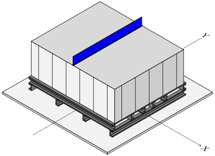
- 1 resonator : usual layer's resonance
- 37 resonators : in X resonant direction : drastic change in layer's resonance
- 37 resonators : in Y inert direction : usual resonance peak
- City impedance analysis : qualitatively and quantitatively accurate

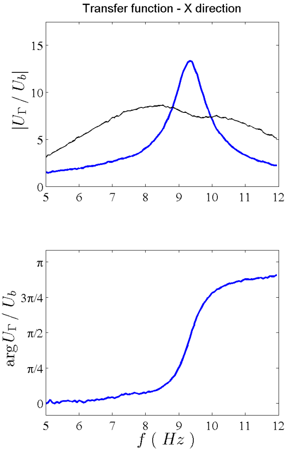
Drastic changes in records

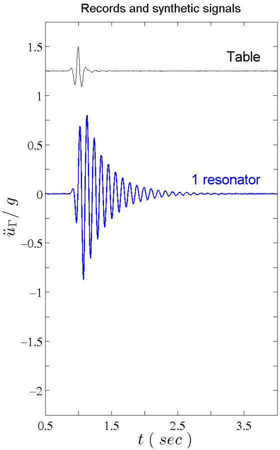


Drastic changes in records

1 sheet

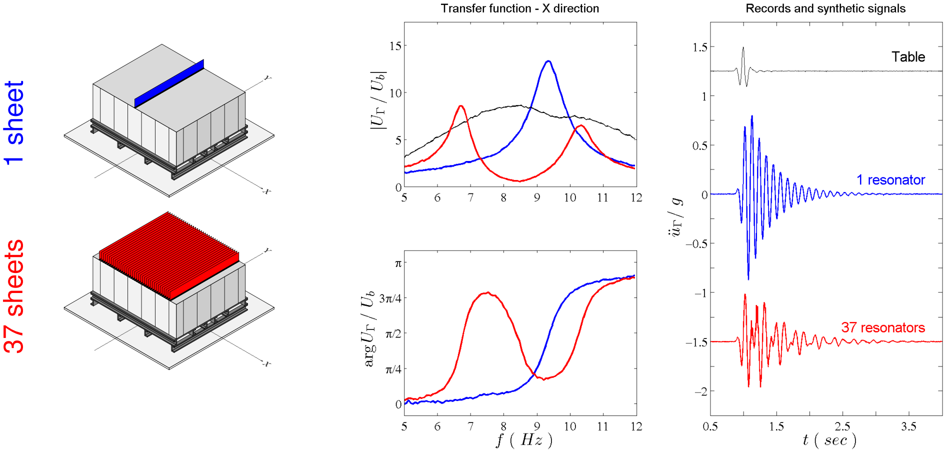






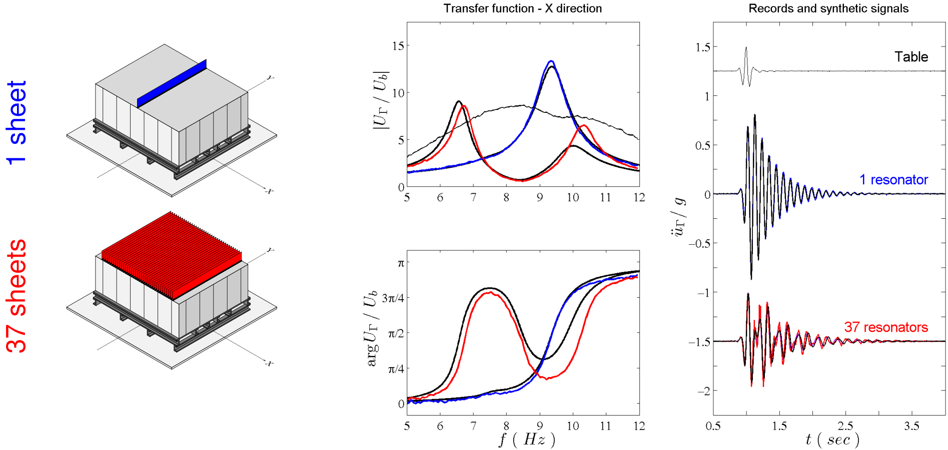
- 1 sheet : usual temporal response of a layer

Drastic changes in records



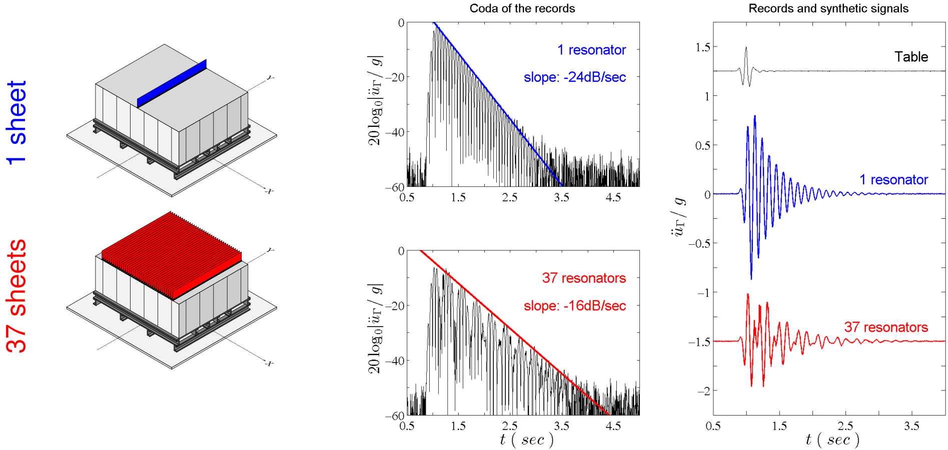
- 1 sheet : usual temporal response of a layer
- 37 sheets : drastic change in shape of records and lower amplitude

Drastic changes in records



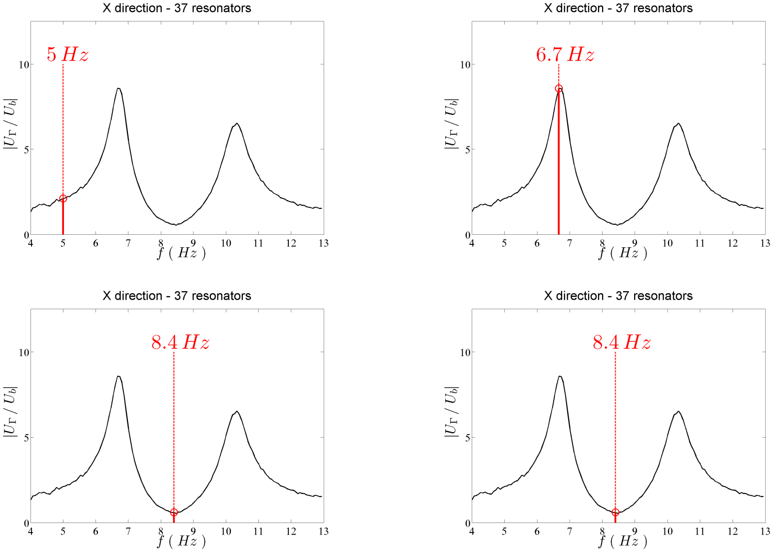
- 1 sheet : usual temporal response of a layer
- 37 sheets : drastic change in shape of records and lower amplitude
- City impedance analysis is accurate temporaly

Drastic changes in records

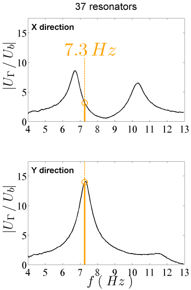


- 1 sheet : usual temporal response of a layer
- 37 sheets : drastic change in shape of records and lower amplitude
- City impedance analysis is accurate temporaly
- Longer coda and clear beatings

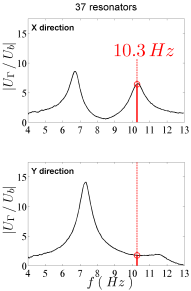
Drastic changes in modal shapes



Depolarization

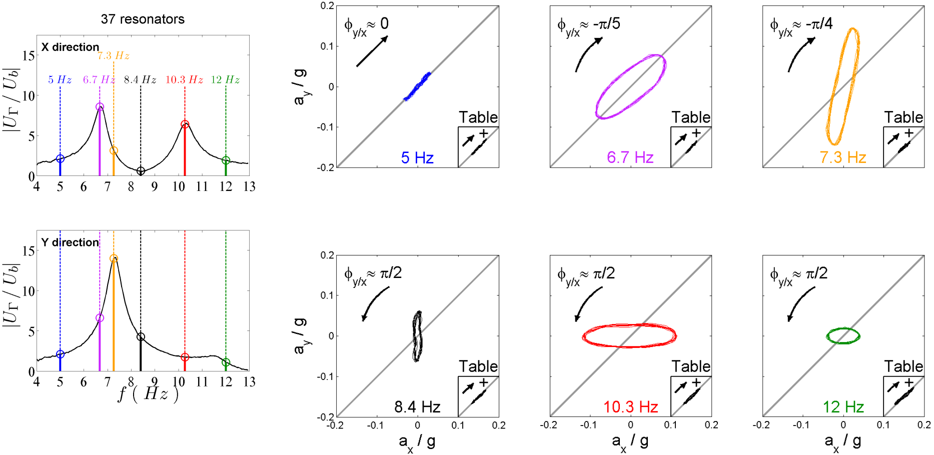


- X : antiresonance
- Y : resonance



- X : resonance
- Y : inertial

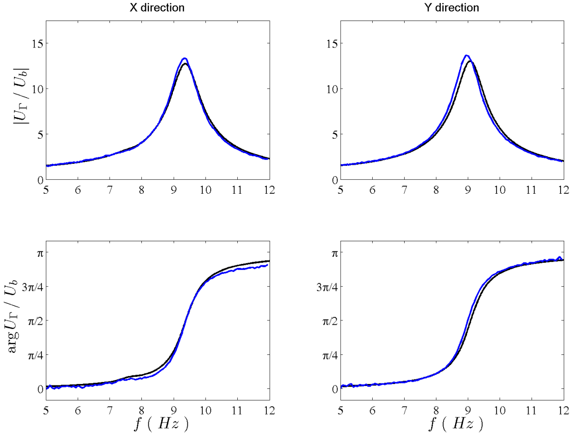
Depolarization

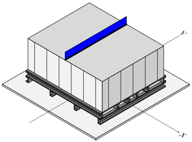


Depolarization :

- frequency-dependent
- due to surface anisotropy
- Affects : direction, ellipticity, orientation

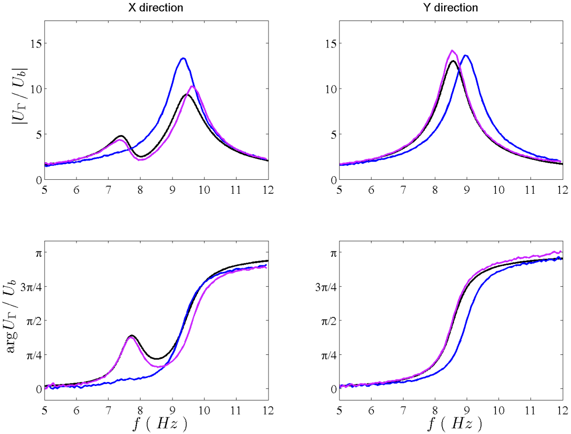
As the city gets denser

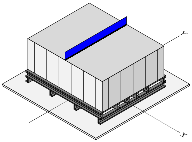




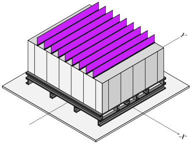
1 sheet

As the city gets denser





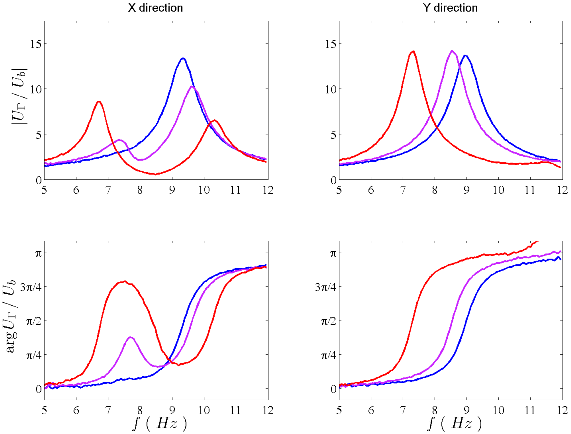
1 sheet



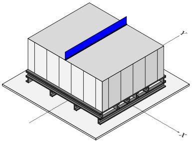
9 sheets
All surface
$\eta = 2.8\%$

- Already significant with 9 structures
- Model applies even for large period ($2\pi\ell/\Lambda \approx 0.4$ for 9 sheets)

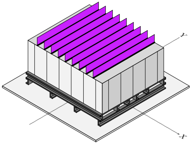
As the city gets denser



- Already significant with 9 structures
- Model applies even for large period ($2\pi\ell/\Lambda \approx 0.4$ for 9 sheets)
- The denser the city, the bigger the effect



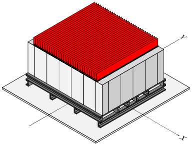
1 sheet



9 sheets

All surface

$\eta = 2.8\%$

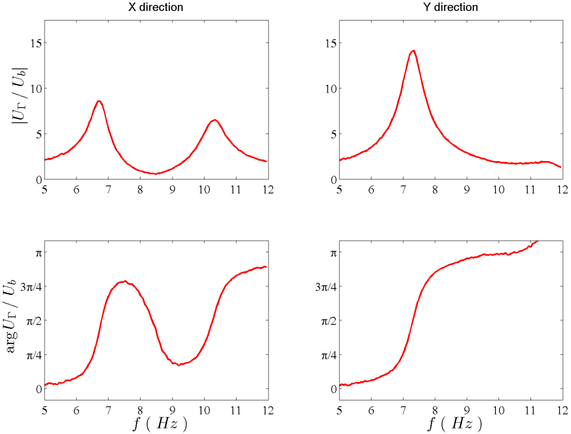


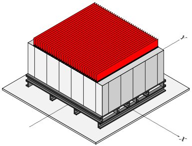
37 sheets

All surface

$\eta = 13.6\%$

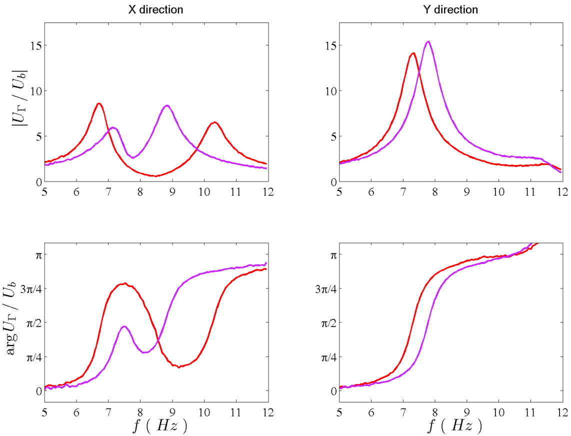
As the city gets smaller

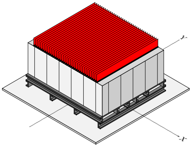




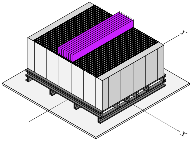
37 sheets
Gathered
$\eta = 13.6\%$

As the city gets smaller





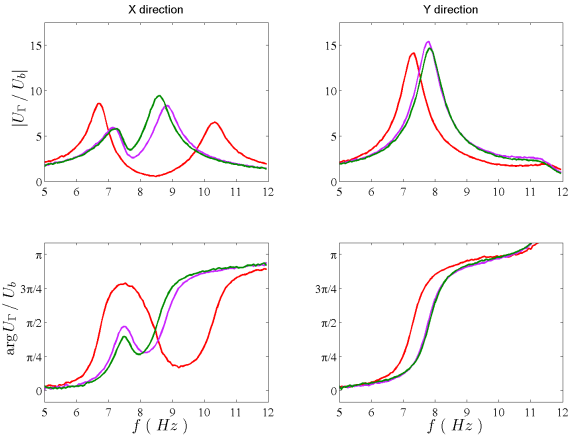
37 sheets
Gathered
$\eta = 13.6\%$

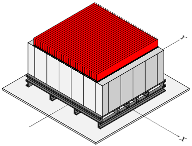


9 sheets
Gathered
$\eta = 13.6\%$

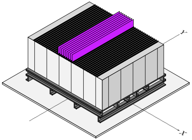
- The smaller the city, the smaller the effect

As the city gets smaller

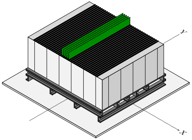




37 sheets
Gathered
$\eta = 13.6\%$



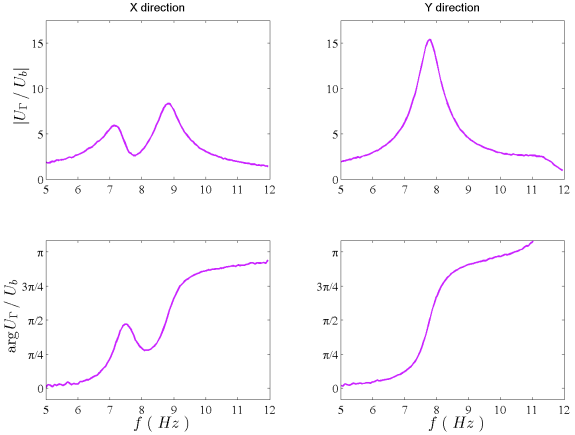
9 sheets
Gathered
$\eta = 13.6\%$

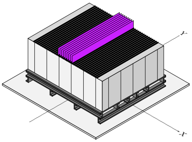


5 sheets
Gathered
$\eta = 13.6\%$

- The smaller the city, the smaller the effect
- Still significant with only 5 structures

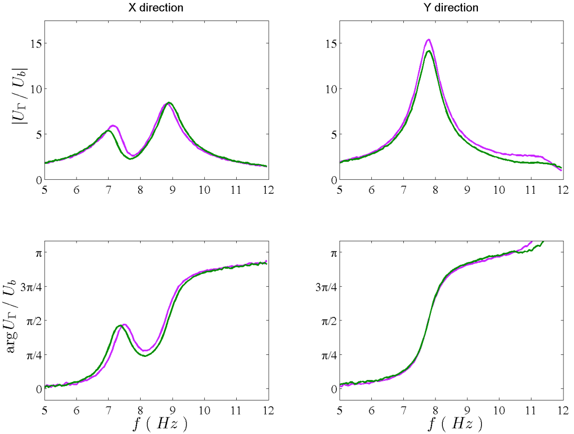
Various distributions of 9 resonators

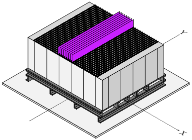




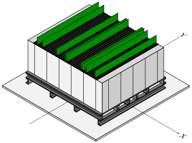
9 sheets
Gathered

Various distributions of 9 resonators





9 sheets
Gathered



9 sheets
Randomly

9 sheets random $\approx$ 9 sheets gathered

Periodic condition is not mandatory

Outline

Theoretical model : city impedance analysis

Design, shaking and instrumentation

Experimental results / city impedance analysis

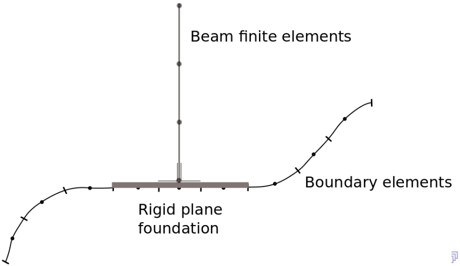
Numerical simulations / city impedance analysis

L.A. Padròn, J.J. Aznàrez & O. Maeso

Conclusions

Numerical simulation with a BEM-FEM model

- The foam block is analyzed using a harmonic 2D direct boundary element formulation leading to a matrix form of the discretized boundary integral equation of the type $\mathbf{Hu} = \mathbf{Gt}$, where $\mathbf{u}$ and $\mathbf{t}$ are the vectors of displacements and tractions ; and $\mathbf{H}$ and $\mathbf{G}$ are the coefficient matrices arising from the BEM.
- Quadratic 3-noded boundary elements are used in meshing the block
- Resonators are modelled using 2-node 6-dof beam finite elements
- Resonators and block are linked by perfectly-bonded rigid surfaces



Numerical simulation with a BEM-FEM model

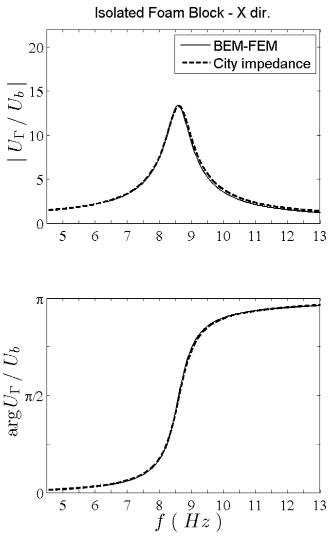
Considering equilibrium and compatibility conditions in the coupling, applying boundary conditions and reordering, the equations describing the dynamic response of the system can be written as

$$\begin{bmatrix} \mathbf{K}_{oo} & \mathbf{K}_{ob} & \mathbf{0} & \mathbf{0} \\ \mathbf{K}_{bo} & \mathbf{K}_{bb} & \mathbf{C} & \mathbf{0} \\ \mathbf{0} & \mathbf{H}_{fc}\mathbf{D} & -\mathbf{G}_{fc} & \mathbf{A}_{ff} \\ \mathbf{0} & \mathbf{H}_{cc}\mathbf{D} & -\mathbf{G}_{cc} & \mathbf{A}_{cf} \end{bmatrix} \begin{Bmatrix} \mathbf{u}^o \\ \mathbf{u}^b \\ \mathbf{t}^c \\ \mathbf{x}^f \end{Bmatrix} = \begin{Bmatrix} \mathbf{f}^o \\ \mathbf{0} \\ \mathbf{f}^{ff} \\ \mathbf{f}^{cf} \end{Bmatrix} \qquad (1)$$

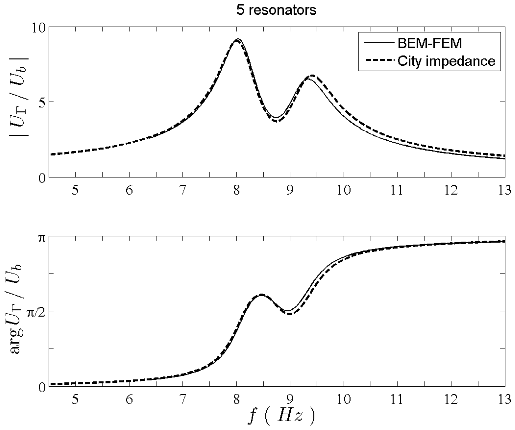
where

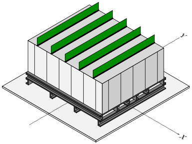
- c and b refer to BEM and FEM nodes in the coupling, and f and o to the ones outside
- $\mathbf{u}$ and $\mathbf{f}$ are the vectors of displacements and external forces
- $\mathbf{K} = \mathbf{K}^* - \omega^2\mathbf{M}$
- **D** and **C** matrices defining the compatibility and equilibrium of the rigid interface
- and $\mathbf{x}^f$ the rest of BEM unknowns

Agreement between numerical and analytical models



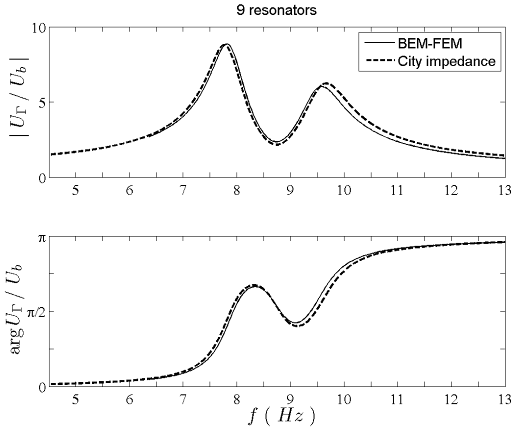
Agreement between numerical and analytical models

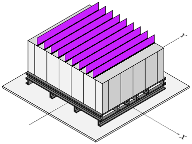




5 sheets
All surface

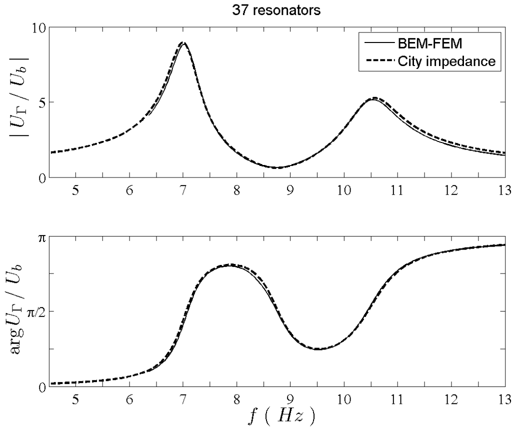
Agreement between numerical and analytical models

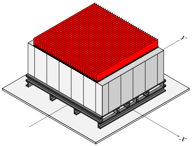




9 sheets
All surface

Agreement between numerical and analytical models





37 sheets
All surface

Outline

Theoretical model : city impedance analysis

Design, shaking and instrumentation

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Numerical simulations / city impedance analysis

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Conclusions

Conclusions

- Multiple interactions phenomena exist and can be significant
- Physical, theoretical and numerical models are validated
- Signatures of the phenomena are identified
- Phenomena are robust (only 5 structures seems sufficient)
- Theory gives the key parameters to quantify the effects
- Application to strongly non-linear soil is out of scope
- Other configurations have been tested within the project

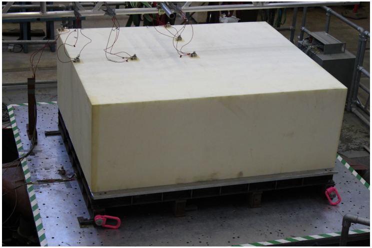
Back to Impedance Back to Design Back to Experiment Back to BEM-FEM Appendix

Appendix

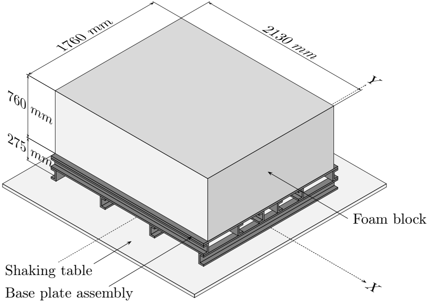
- Cellular poylurethan foam
- Edge rods
- Modal shapes
- City gets denser
- City gets smaller
- Distributions of 9 resonators
- City with two types of resonators
- Other videos
- Other depolarizations

Material : Cellular polyurethan foam Appendix

- Homogeneous and light : $\rho = 49kg/m^3$
- Elastic linear, isotropic and soft : $E \approx 118kPa \quad \nu \approx 0.1$
- No need for a container, clean, cheap, recyclable

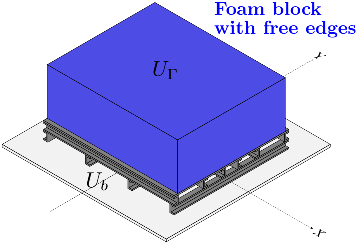


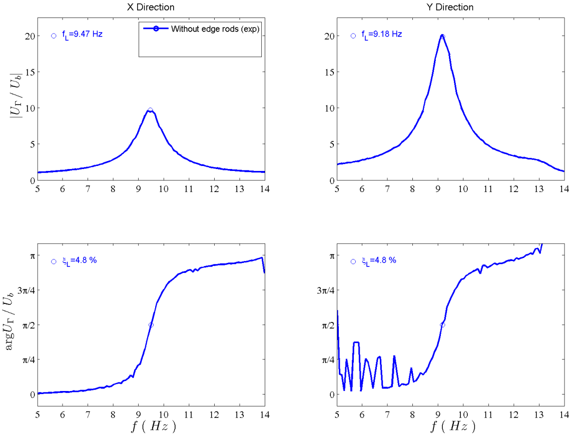
Size



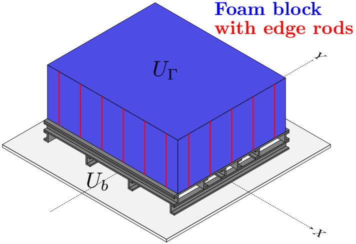
- $L \times B \times H = 2.13m \times 1.76m \times 0.76m$
- Aspect ratios : $L/H = 2.8$ and $B/H = 2.3$
- Total mass : $140\,kg$ (without the base plate assembly)

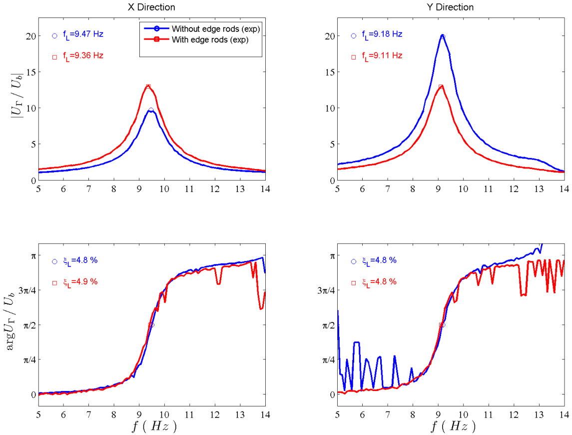
Design of the edge rods Appendix





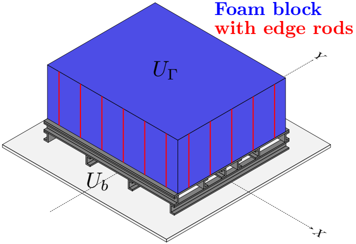
Design of the edge rods Appendix

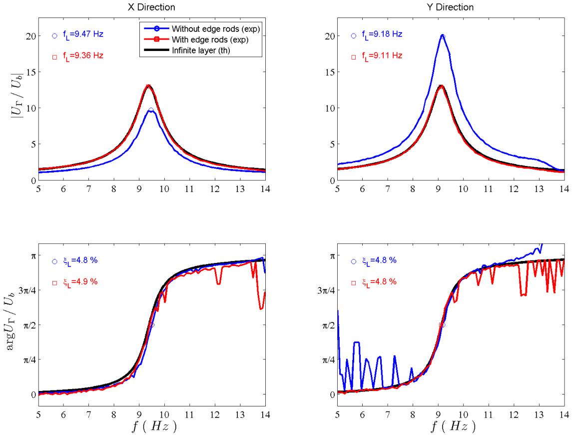




- 3 *mm*-diameter 75 *cm*-long vertical steel rods are adhered at 35 *cm* centres around the periphery of the foam block
- Diameter and spacing designed to limit boundary effects

Design of the edge rods Appendix





Infinite layer :

$$\frac{U_\Gamma}{U_b} = \frac{1}{\cos\left(\dfrac{\frac{\pi}{2}\frac{f}{f_L}}{\sqrt{1-i2\xi_L}}\right)}$$

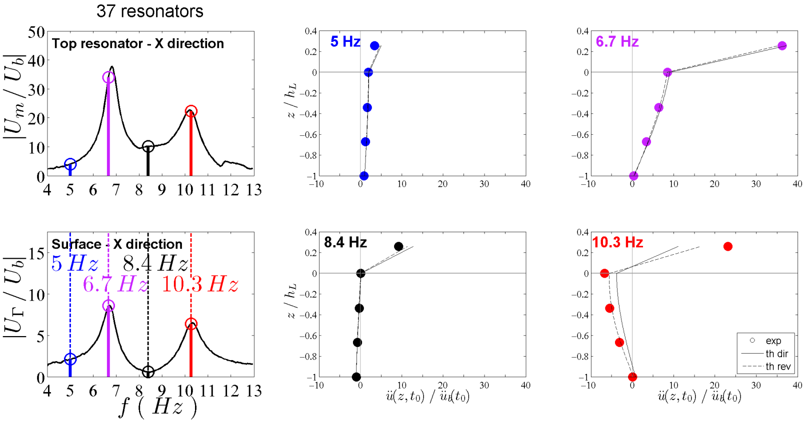
$f_L = 9.36\ Hz$ in X

$f_L = 9.11\ Hz$ in Y

$\xi_L = 4.9\%$ in X and Y

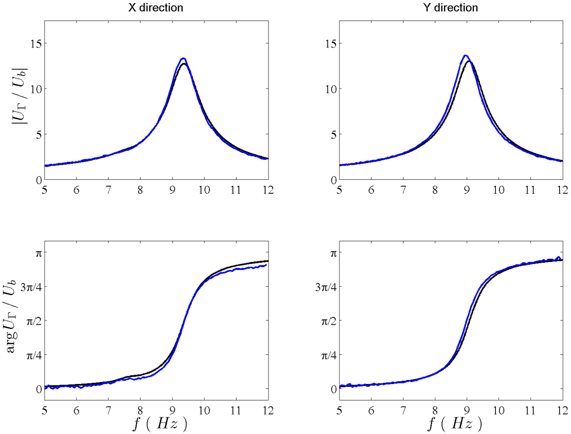
- Eigenfrequency and damping remain unchanged
- The transfer function U_Γ / U_b is the one of a theoretical infinite layer

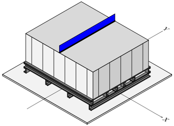
Modal shapes Appendix



- At both resonance peaks : usual wave-quarter shape for layer
- 1^{st} resonance peak : oscillators in phase with layer
- 2^{nd} resonance peak : oscillators in phase opposition with layer
- At surface antiresonance : oscillators in resonance

As the city gets denser Appendix



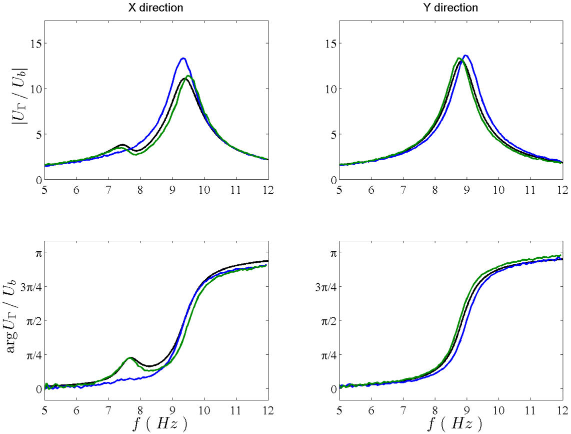


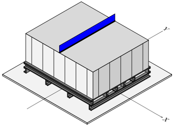
1 sheet

All surface

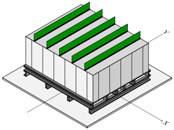
$\eta = 0.2\%$

As the city gets denser Appendix





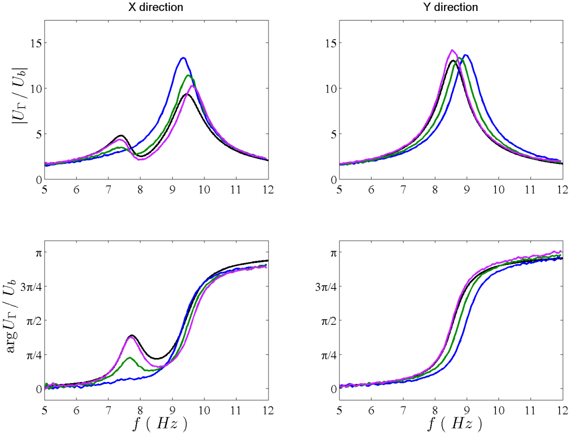
1 sheet
All surface
$\eta = 0.2\%$

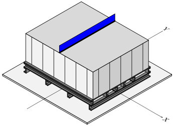


5 sheets
All surface
$\eta = 1.4\%$

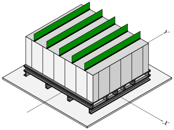
▶

As the city gets denser Appendix

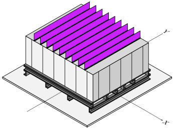




1 sheet
All surface
$\eta = 0.2\%$



5 sheets
All surface
$\eta = 1.4\%$

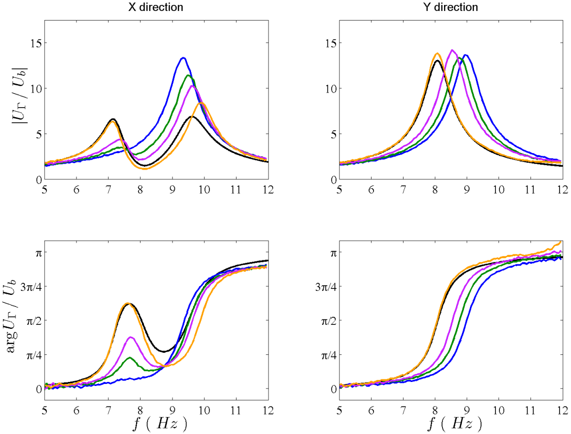


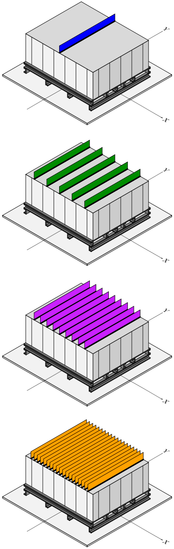
9 sheets
All surface
$\eta = 2.8\%$

-
-
-

As the city gets denser

Appendix



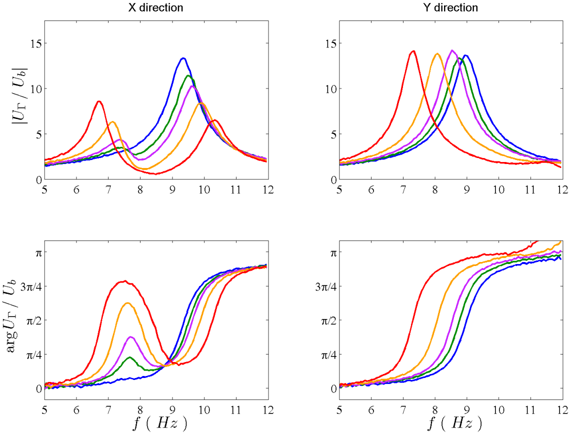


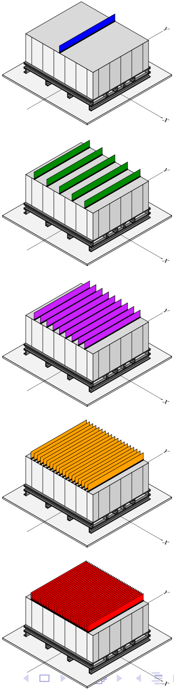
▶

▶

▶

As the city gets denser Appendix





1 sheet
All surface
$\eta = 0.2\%$

5 sheets
All surface
$\eta = 1.4\%$

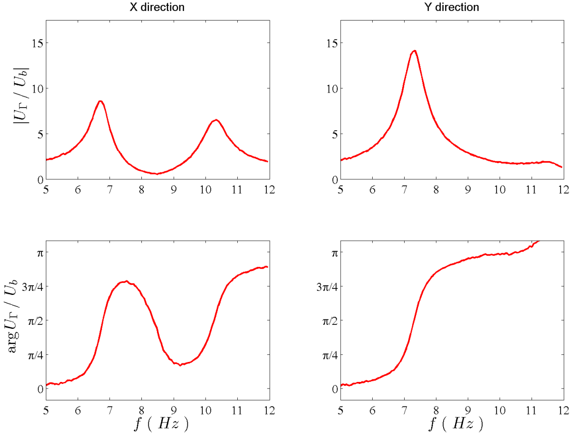
9 sheets
All surface
$\eta = 2.8\%$

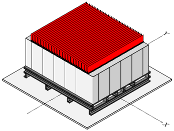
19 sheets
All surface
$\eta = 6.0\%$

37 sheets
All surface
$\eta = 13.6\%$

-
-
-

As the city gets smaller Appendix

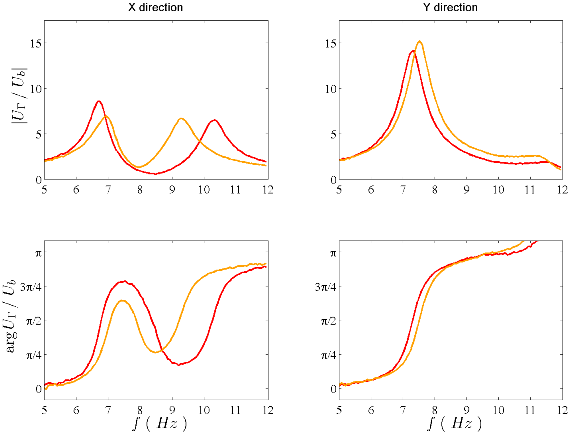


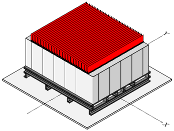


37 sheets
Gathered
$\eta = 13.6\%$

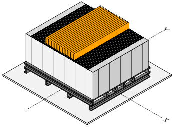
▶

As the city gets smaller Appendix





37 sheets
Gathered
$\eta = 13.6\%$



19 sheets
Gathered

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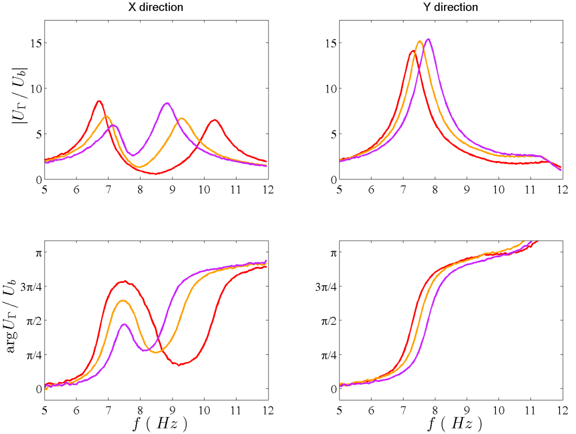
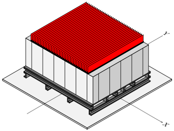
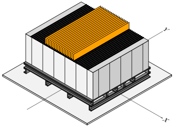
-

As the city gets smaller Appendix

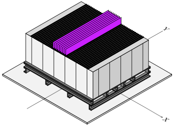




37 sheets
Gathered
$\eta = 13.6\%$



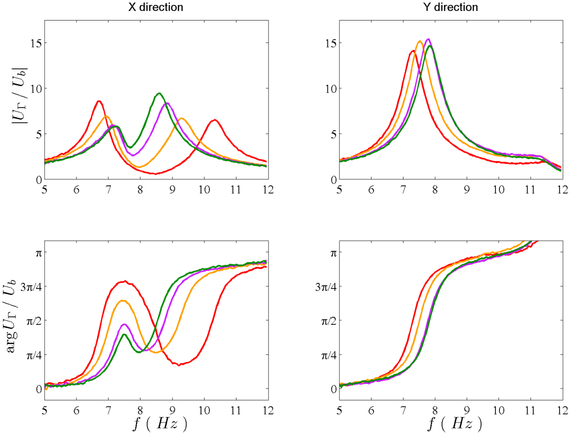
19 sheets
Gathered

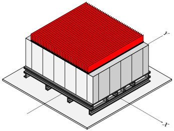


9 sheets
Gathered

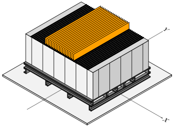
-
-

As the city gets smaller Appendix

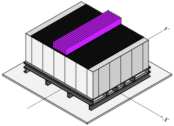




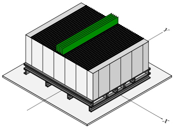
37 sheets
Gathered
$\eta = 13.6\%$



19 sheets
Gathered



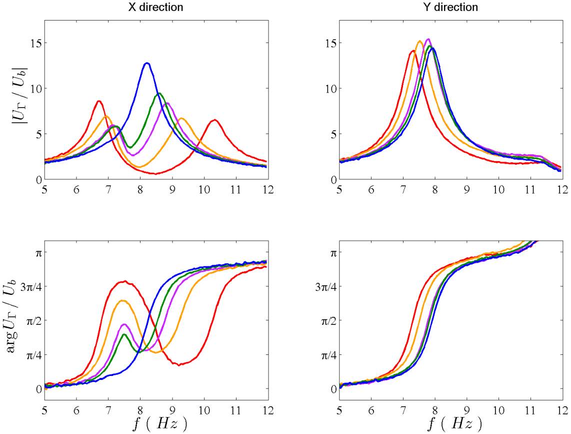
9 sheets
Gathered

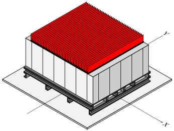


5 sheets
Gathered

As the city gets smaller

Appendix

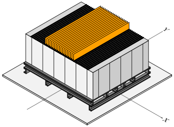




37 sheets

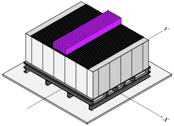
Gathered

$\eta = 13.6\%$



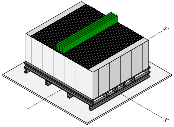
19 sheets

Gathered



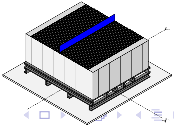
9 sheets

Gathered



5 sheets

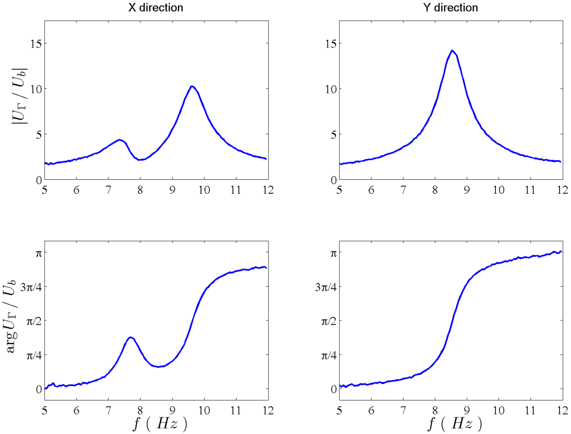
Gathered

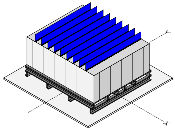


1 sheet

-
-
-
-

Various distributions of 9 resonators Appendix

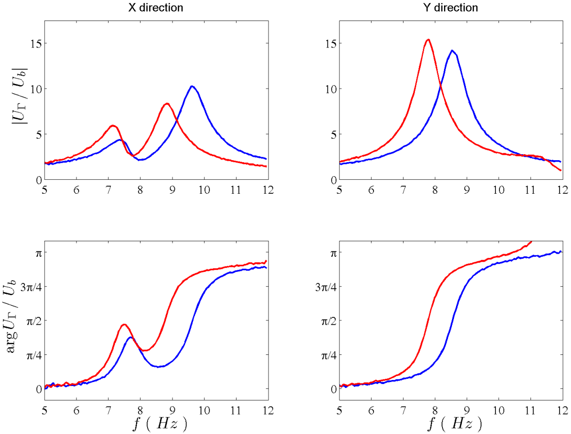


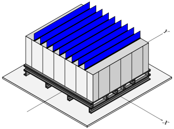


9 sheets
All surface
$\eta = 2.8\%$

▶

Various distributions of 9 resonators Appendix

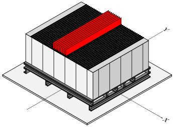




9 sheets

All surface

$\eta = 2.8\%$

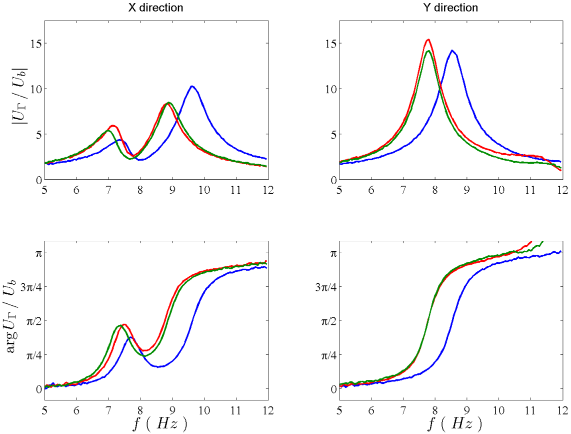


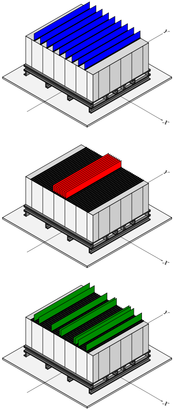
9 sheets

Gathered

-
-

Various distributions of 9 resonators [Appendix]





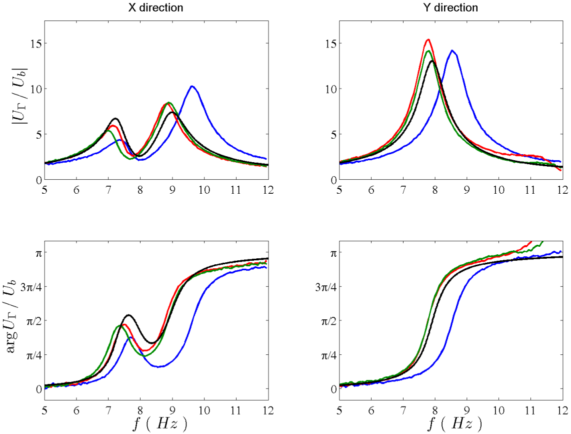
9 sheets
All surface
$\eta = 2.8\%$

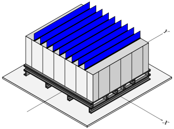
9 sheets
Gathered

9 sheets
Randomly

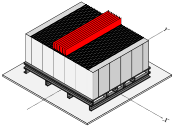
-
-
-

Various distributions of 9 resonators Appendix

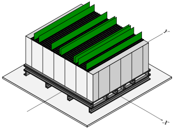




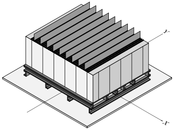
9 sheets
All surface
$\eta = 2.8\%$



9 sheets
Gathered

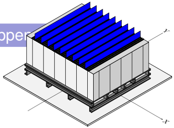


9 sheets
Randomly



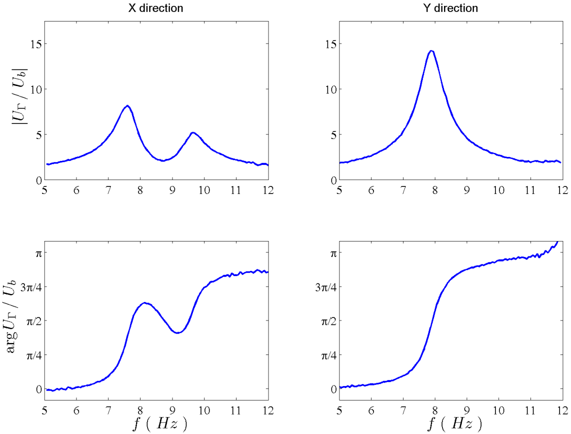
9 sheets
+ all angles
All surface
Theoric
$\eta = 3.1\ \%$

City with two types of resonators Appendix

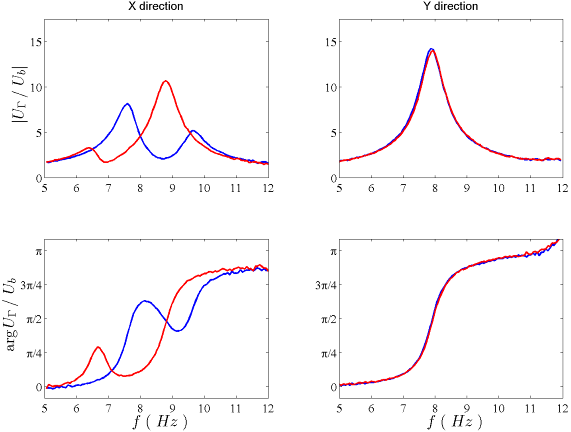


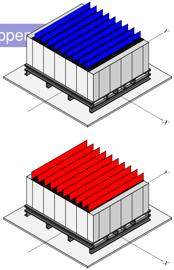
9 smaller

$h_o = 17.2\ cm$



City with two types of resonators





9 smaller

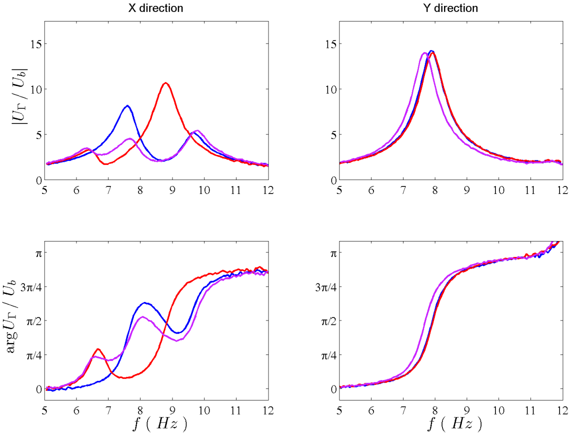
$h_o = 17.2\ cm$

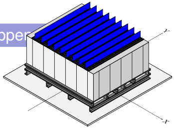
10 bigger

$h_o = 19.8\ cm$

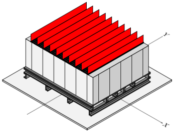
- $\neq$ oscillators eigenfrequency $\Rightarrow \neq$ shapes

City with two types of resonators

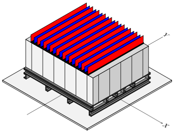




9 smaller
$h_o = 17.2\ cm$



10 bigger
$h_o = 19.8\ cm$

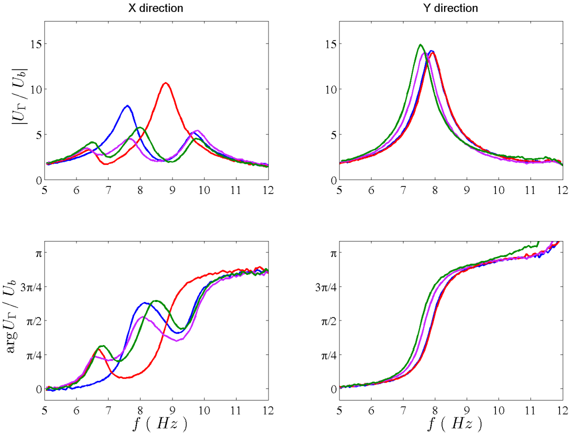


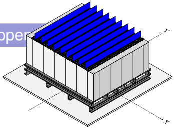
9 smaller
& 10 bigger
Periodically

- $\neq$ oscillators eigenfrequency $\Rightarrow \neq$ shapes
- 2 ANTIRESONANCES (like theory)

City with two types of resonators

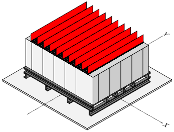
Apper





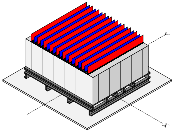
9 smaller

$h_o = 17.2 \ cm$

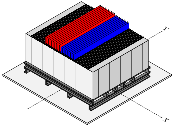


10 bigger

$h_o = 19.8 \ cm$



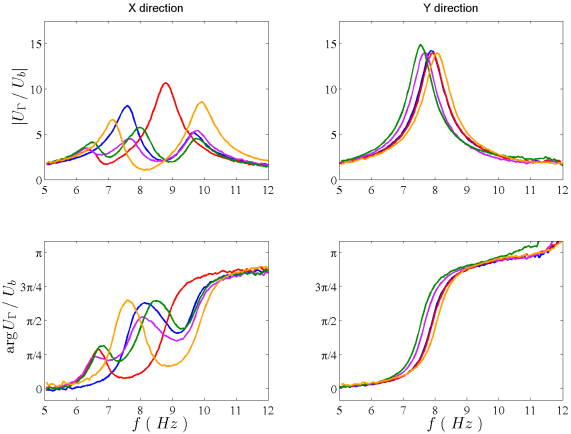
9 smaller
& 10 bigger
Periodically



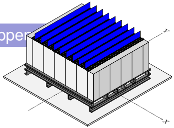
9 smaller
& 10 bigger
Separately

- $\neq$ oscillators eigenfrequency $\Rightarrow \neq$ shapes
- 2 ANTIRESONANCES (like theory)
- Quite the same no matter the distribution

City with two types of resonators

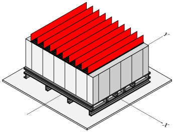


- $\neq$ oscillators eigenfrequency $\Rightarrow \neq$ shapes
- 2 ANTIRESONANCES (like theory)
- Quite the same no matter the distribution
- Same mass, different effects



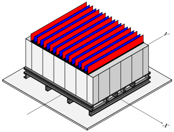
9 smaller

$h_o = 17.2\ cm$

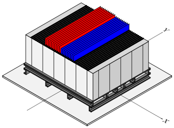


10 bigger

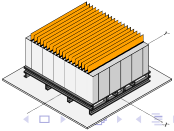
$h_o = 19.8\ cm$



9 smaller
& 10 bigger
Periodically



9 smaller
& 10 bigger
Separately

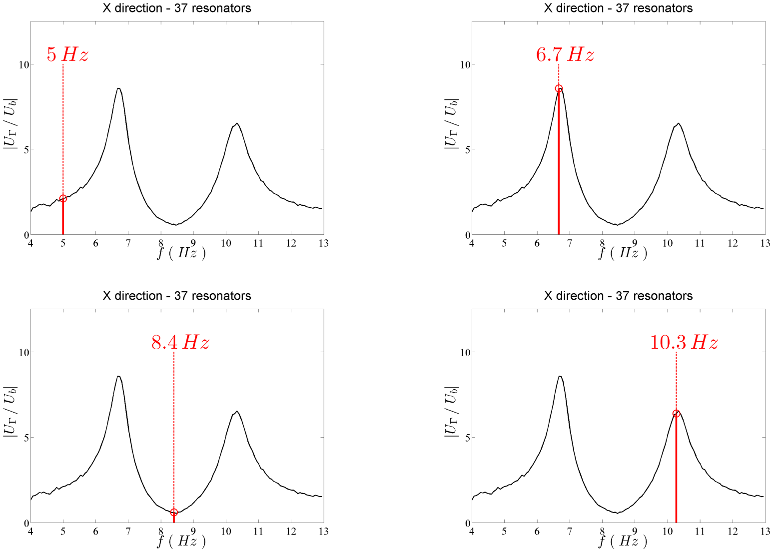


19 medium

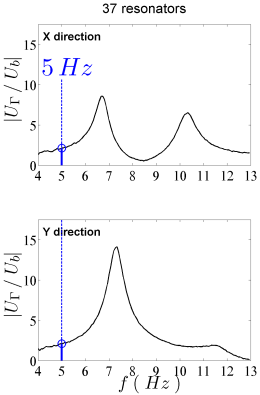
$h_o = 18.4\ cm$

$\eta = 6.0\%$

Videos Appendix

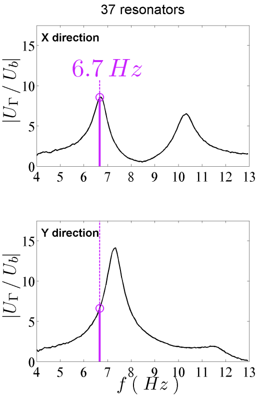


Depolarization Appendix



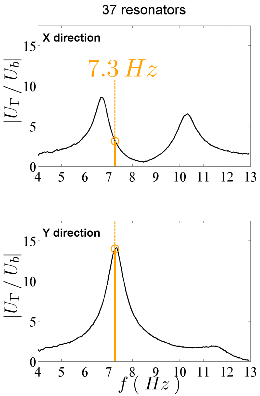
- X : Quasi-static
- Y : Quasi-static

Depolarization Appendix



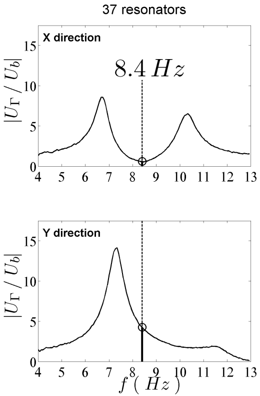
- X : Resonance
- Y : Near resonance

Depolarization Appendix



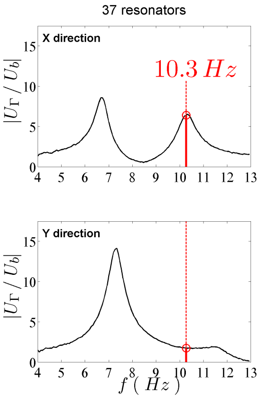
- X : Near anti-resonance
- Y : Resonance

Depolarization Appendix



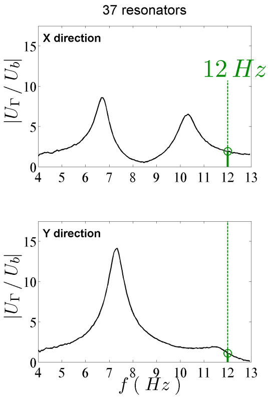
- X : Anti-resonance
- Y : Not so far from resonance

Depolarization Appendix



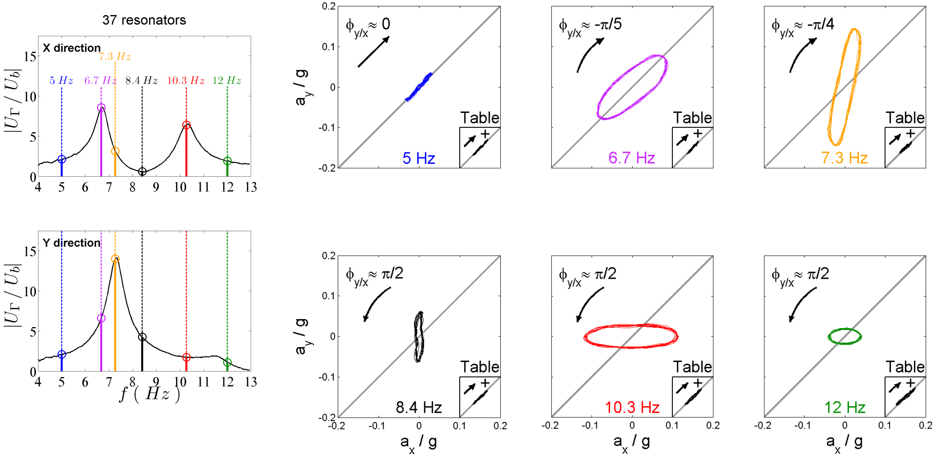
- X : Resonance
- Y : Inertial regime

Depolarization Appendix



- X : Inertial regime
- Y : Inertial regime

Depolarization Appendix



- frequency-dependent
- due to surface anisotropy
- Affects : direction, ellipticity, orientation