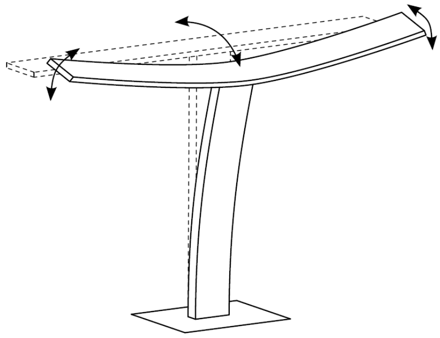
Damping by branching of flexible structure: a bioinspiration from trees



presented by Benoit Theckes

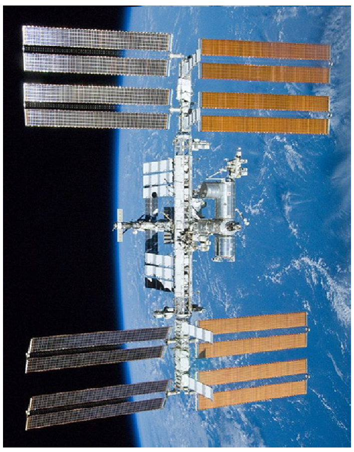
Directed by
Emmanuel de Langre (LadHyX)
Xavier Boutillon (LMS)

ÉCOLE POLYTECHNIQUE ParisTech

OPÉRATION MÉCANIQUE ET SYSTÈMES VIVANTS

DGA

Harmfull vibrations



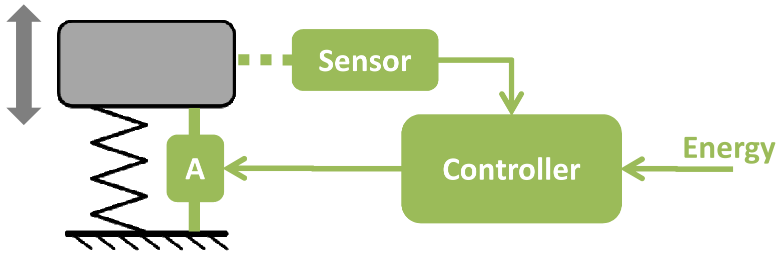
ISS

Fonctionnality loss and dammage

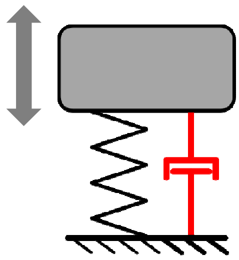
Noise, wear

One solution: damping

- Active means:



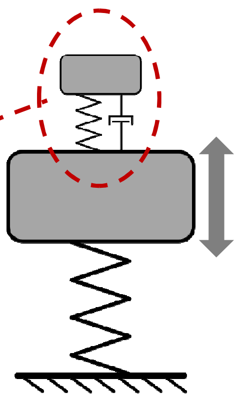
- Passive means:



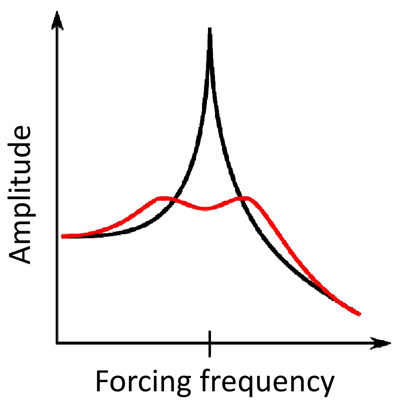
Example of application

The Tuned-Mass-Damper

Example of application



Principle

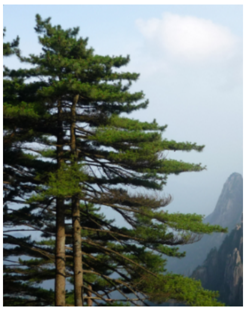


Performance

Restriction: damping rate brougth by TMD is not amplitude-dependant

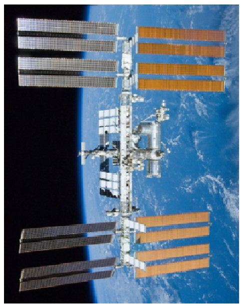
Question:

How to design passive damping mecanisms, specific to damp large amplitude vibrations ?



Trees

Bioinspired approach



Man-made structures

Damping of large amplitude motions

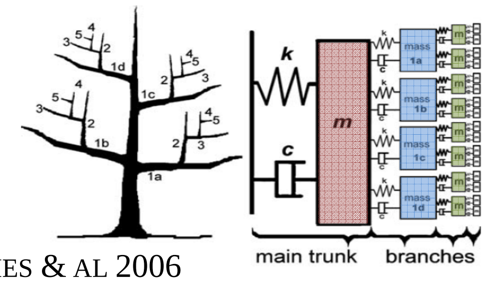
A matter of survival for trees

Pull and realease test on a Maple tree by KANE

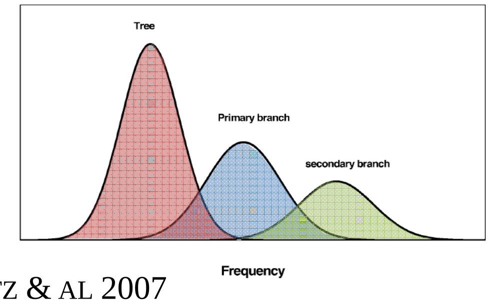
- Wood behavior
- Aerodynamic effects
- …

Branching role in the linear tree dynamics

- Coupled tree model:



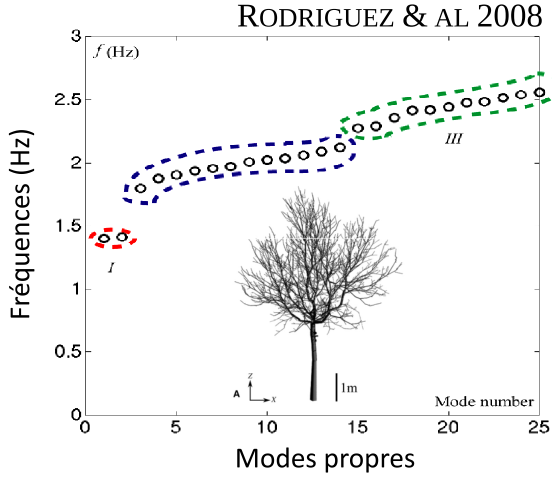
JAMES & AL 2006



SPATZ & AL 2007

- Modal dynamics:

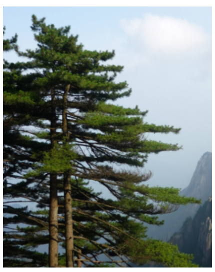
RODRIGUEZ & AL 2008



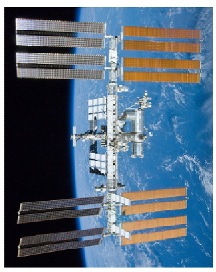
The role of branches in the <u>non-linear dynamics</u> ?

Thesis

Branching in flexible structures offers a **robust** damping mecanism, **specific** to **large amplitude** vibrations



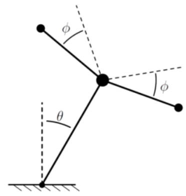
In trees



In man-made structures

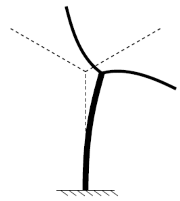
Plan

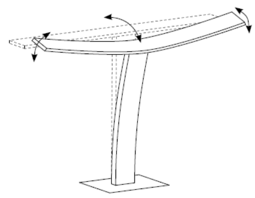
I – Elementary branched model



II – Robustness

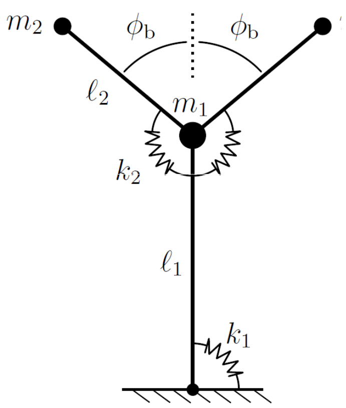
III – Continuous branched structures



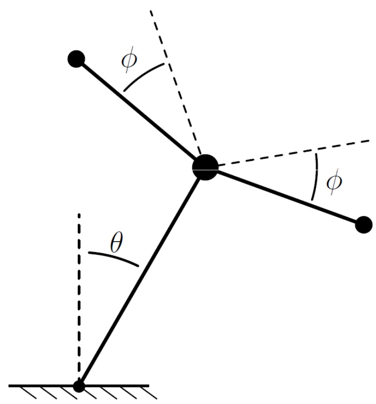


IV – Two proposals of application

Elementary branched model

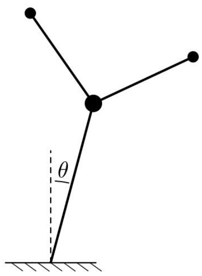


Geometry

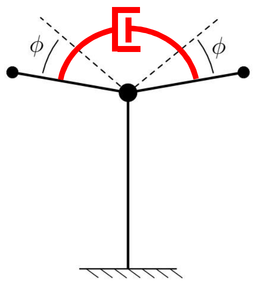


Motion

Equations



Trunk mode



Branches mode

- Frequency ratio $\Omega = \dfrac{\omega_{\mathrm{Branches}}}{\omega_{\mathrm{Tronc}}}$
- Inertia ratio Γ
- Branching angle ϕ_{b}
- Damping rate ξ_{b}

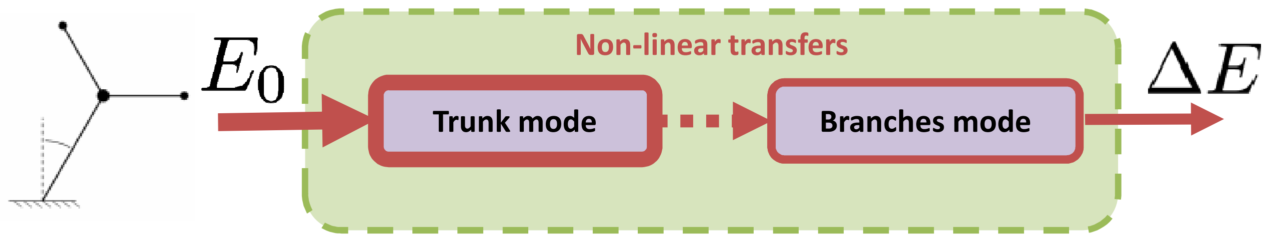
$$\ddot\Theta + \Theta = 2\Gamma\left[\dot\Theta\,\dot\Phi\,\sin(\phi_{\mathrm{b}}+\Phi) - \ddot\Theta\left(\cos(\phi_{\mathrm{b}}+\Phi) - \cos\phi_{\mathrm{b}}\right)\right],$$

$$\ddot\Phi + 2\xi_{\mathrm{b}}\Omega\,\dot\Phi + \Omega^2\,\Phi = -\dot\Theta^2\,\sin(\phi_{\mathrm{b}}+\Phi)\,.$$

Pull and Release on the trunk

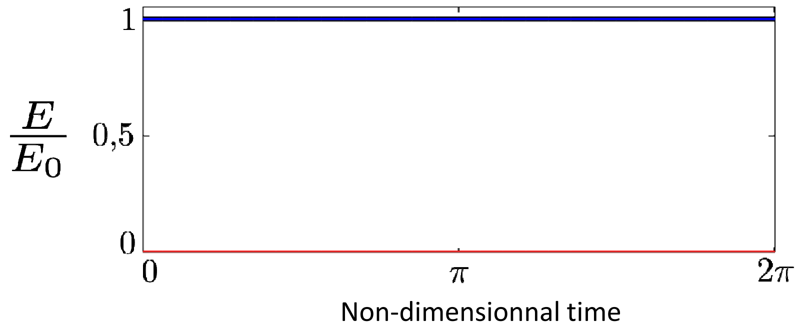
- Linear case:

- Non-linear case:

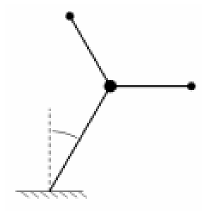


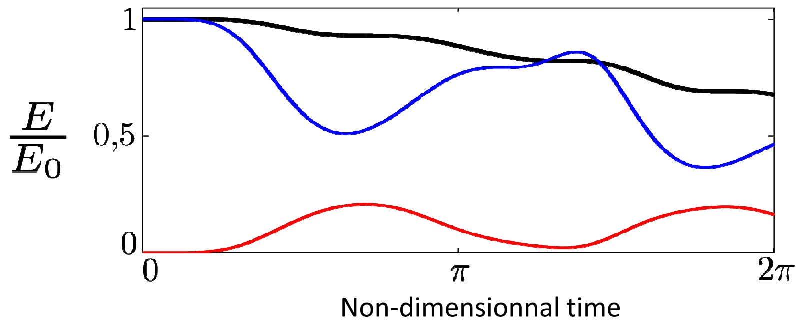
Damping by branching

- Linear case:

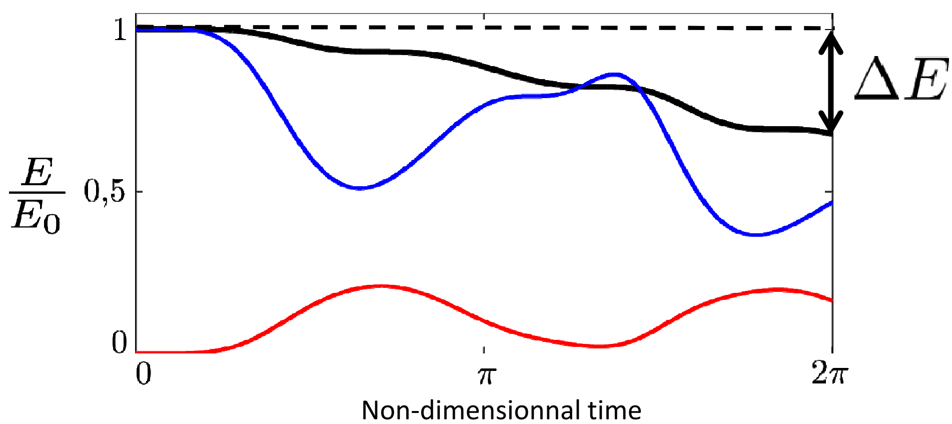


- Non-linear case:





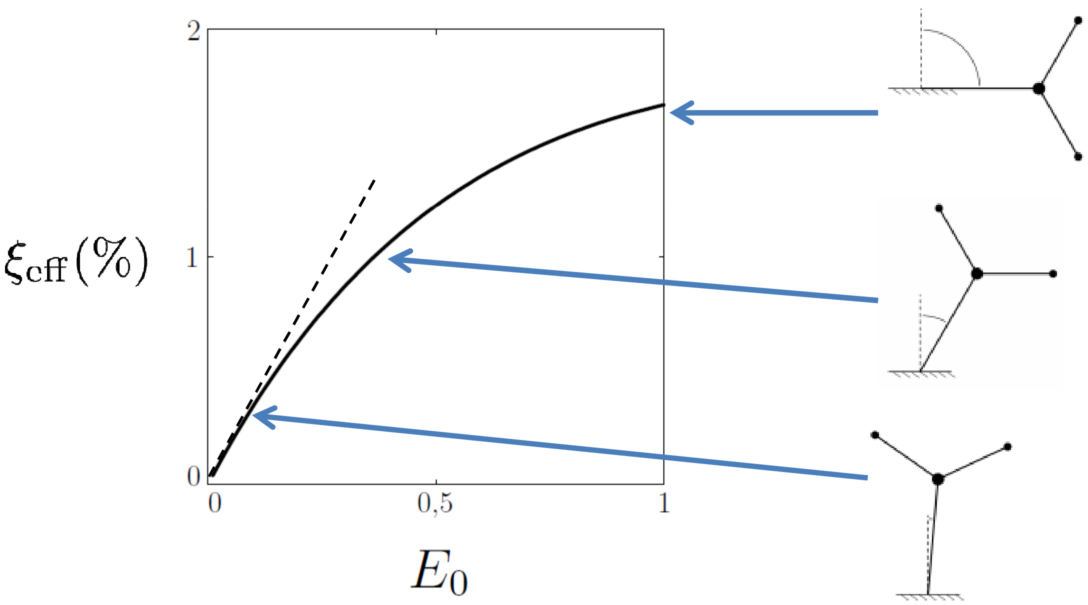
Arbitrary definition



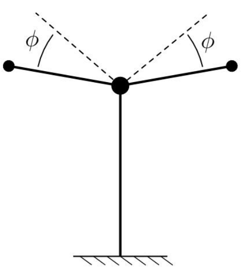
- Defined from the global loss of the total energy in one oscillation of the trunk:

$$\xi_{\text{eff}} = \frac{1}{4\pi}\frac{\Delta E}{E_0}$$

Increases with energy



First-order non-linearities



The system of two equations is simplified to:

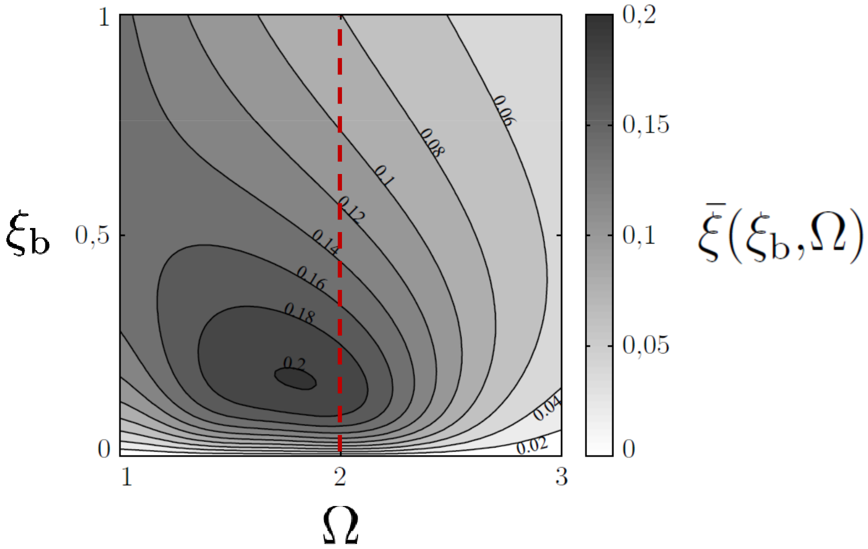
$$\ddot{\Phi}(t) + \boxed{\Omega^2}\Phi(t) = E_0 \sin^2\phi_{\mathrm{b}} \boxed{\cos 2t}$$

Internal non-linear resonance if $\Omega = 2$

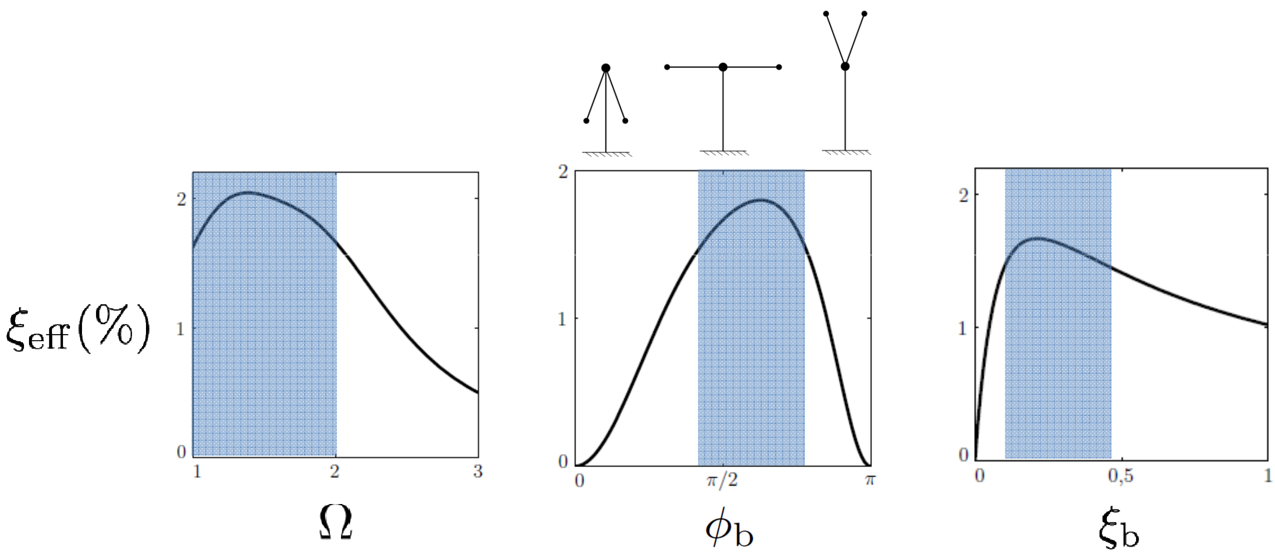
$$\xi_{\mathrm{eff}} = E_0\,\Gamma\,\sin^2\phi_{\mathrm{b}}\;\bar{\xi}(\xi_{\mathrm{b}},\Omega)$$

Analytic results

$$\xi_{\text{eff}} = E_0\,\Gamma\,\sin^2\phi_{\text{b}}\;\underline{\bar{\xi}(\xi_{\text{b}},\Omega)}$$



Parameters dependency



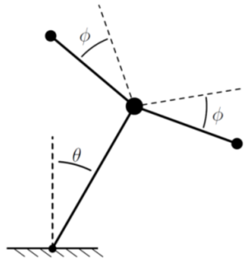
Wide range of optimal values

Conclusion

Elementary branched model

Damping by branching :

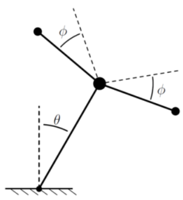
- Increases with the amplitude of motion.
- It is based on a centrifugal excitation of the branches from the trunk motion (Résonnance interne 1:2).
- It depends on four non-dimensionnal parameters:
  - Frequency ratio
  - Rotationnal inertia ratio
  - Damping rate of the branches mode
  - Branching angle



- It brings typically 2% additionnal damping rate for large amplitude motions in a wide range of parameters values.

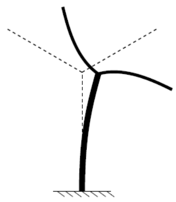
Plan

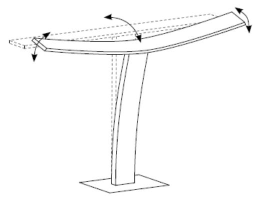
I – Elementary branched model



II – Robustness

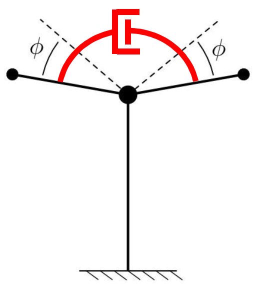
III – Continuous branched structures

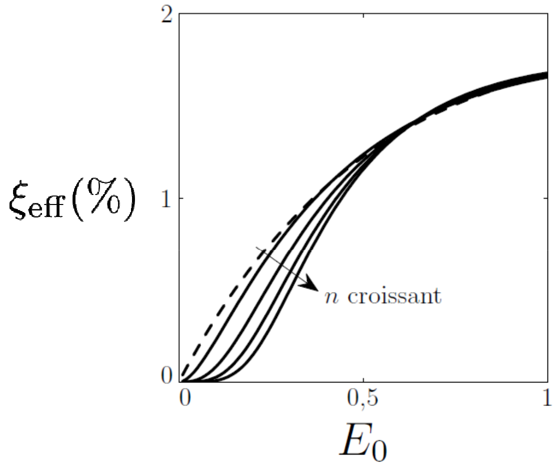




IV – Two proposals of application

Non-linear damping on the branches mode

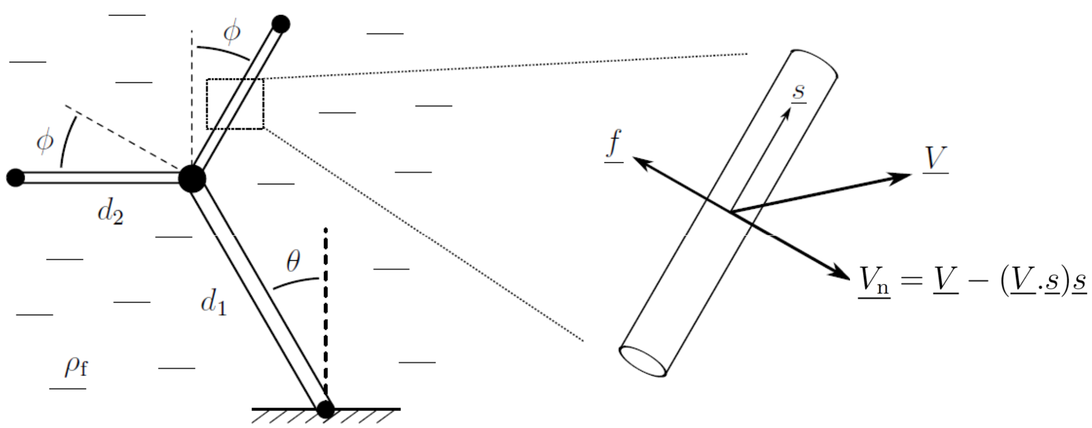




$$\ddot{\Theta} + \Theta = 2\Gamma\left[\dot{\Theta}\,\dot{\Phi}\,\sin(\phi_\text{b}+\Phi) - \ddot{\Theta}\big(\cos(\phi_\text{b}+\Phi) - \cos\phi_\text{b}\big)\right],$$

$$\ddot{\Phi} + \underline{2\Omega\xi_\text{b}\,\dot{\Phi}|\dot{\Phi}|^{n-1}} + \Omega^2\,\Phi = -\dot{\Theta}^2\,\sin(\phi_\text{b}+\Phi)\,,$$

Aerodynamic damping



Oscillations in a fluide at rest

$$\underline{f_i} = -\frac{1}{2}\,\rho_\text{f}\,C_\text{D}\,d_i\,|\underline{V_\text{n}}|\underline{V_\text{n}}$$

Equations

$$\ddot{\Theta} + \Theta = 2\Gamma\left[\dot{\Theta}\,\dot{\Phi}\,\sin(\phi_b+\Phi) - \ddot{\Theta}\left(\cos(\phi_b+\Phi) - \cos\phi_b\right)\right] + \Gamma\,\mathcal{M}\;\mathrm{Fct}_{\Theta}(\dot{\Theta},\dot{\Phi},\Theta,\Phi),$$

$$\ddot{\Phi} + \Omega^2\,\Phi = -\dot{\Theta}^2\,\sin(\phi_b+\Phi) + \mathcal{M}\;\mathrm{Fct}_{\Phi}(\dot{\Theta},\dot{\Phi},\Theta,\Phi).$$

Mass number $\mathcal{M} = C_D \dfrac{\rho_f d_1 \ell_1^3}{4 m_2 \sqrt{\ell_1 \ell_2}}$

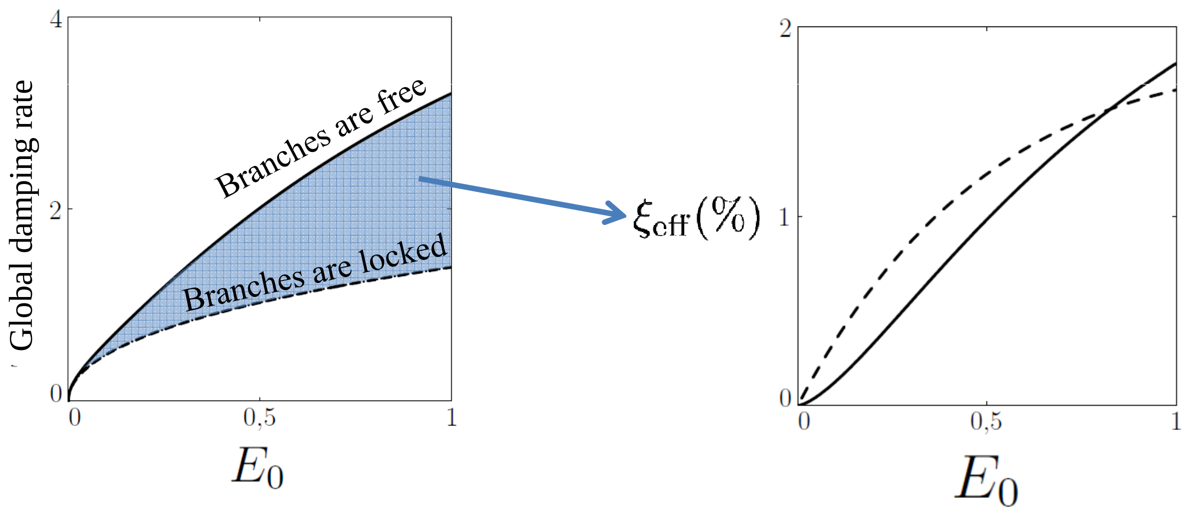
Aerodynamic damping is share on the whole structure: on the branches mode but also on the trunk mode.

→ In this case, how to identify damping by branching ?

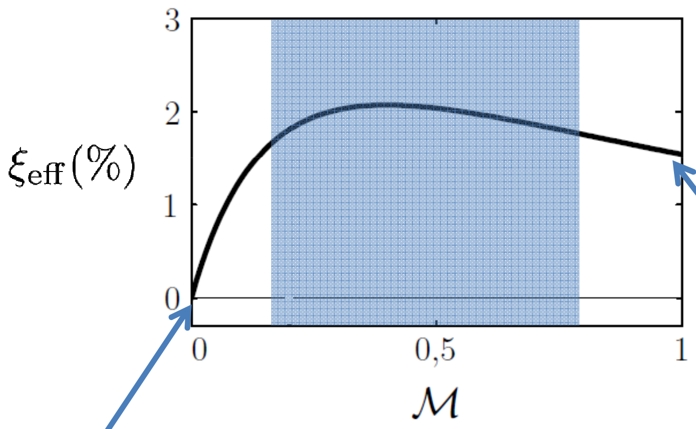
Damping by branching

Comparison between two case:

- Free branches motion
- Locked branches motion



Mass number effect



To much dissipation in the trunk leads to less modal energy transfers

No fluid dissipation results in no damping by branching since the energy cannot be dissipated

Conclusion

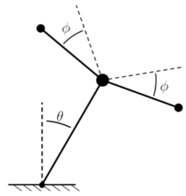
Robustness

Complexifying energy dissipation source:

- New method to identify damping by branching with the comparison between locked and free branches cases.
- Do not disturb damping by branching
- New fluid-linked parameters have a large range of optimal values

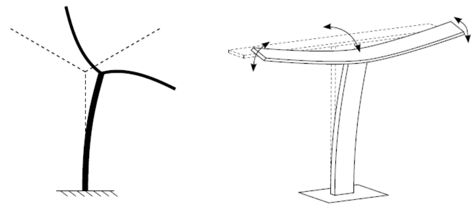
Plan

I – Elementary branched model



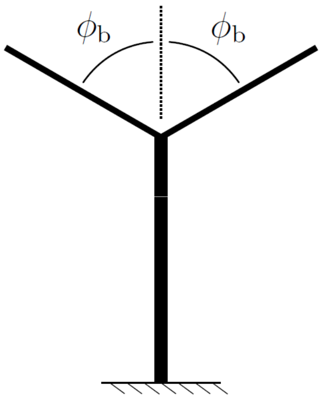
II – Robustness

III – Continuous branched structures



IV – Two proposals of application

Continous branched model

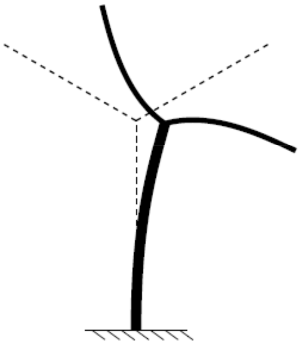


Geometry

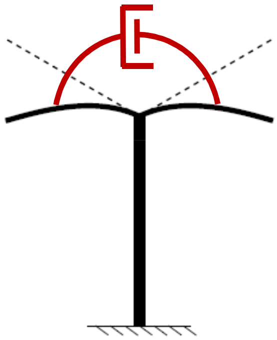
CAST3M software :

- Finite-elements method
- Taking into acount large amplitude motions
- 10 beam elements per segment

Modal dynamics

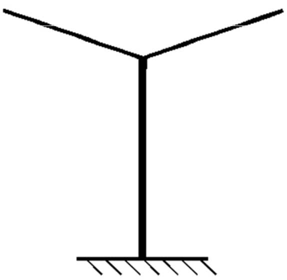


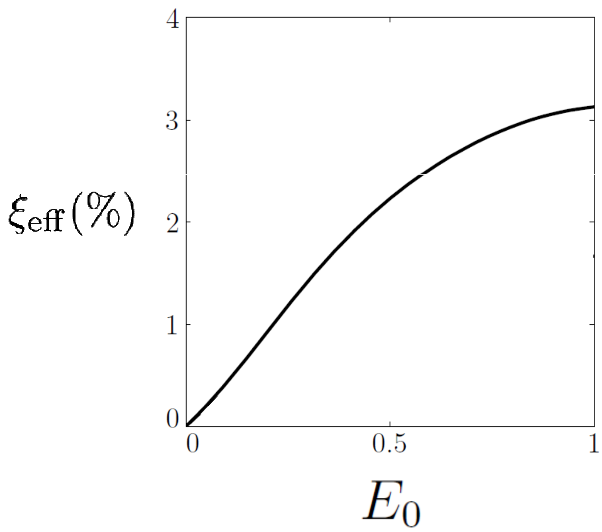
Trunk mode



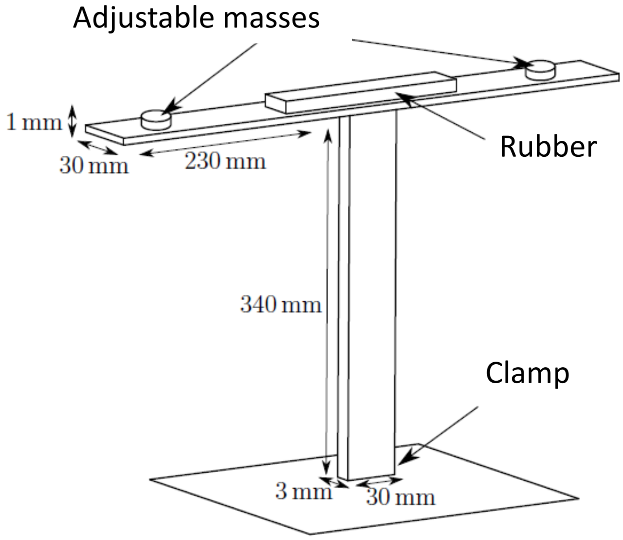
Branches mode

Damping by branching



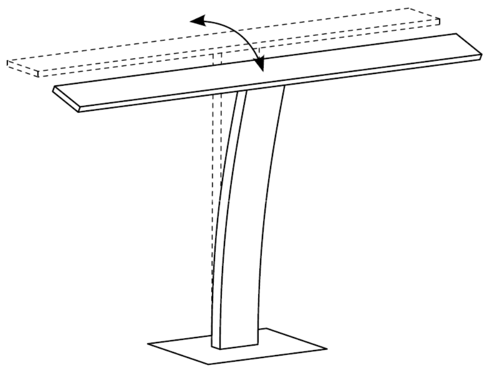


Illustrative experiment

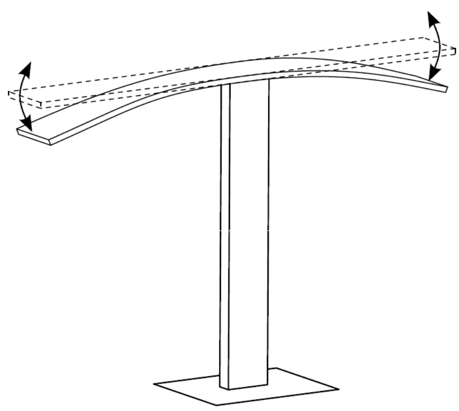


III – Continous branched structures

Modal dynamics



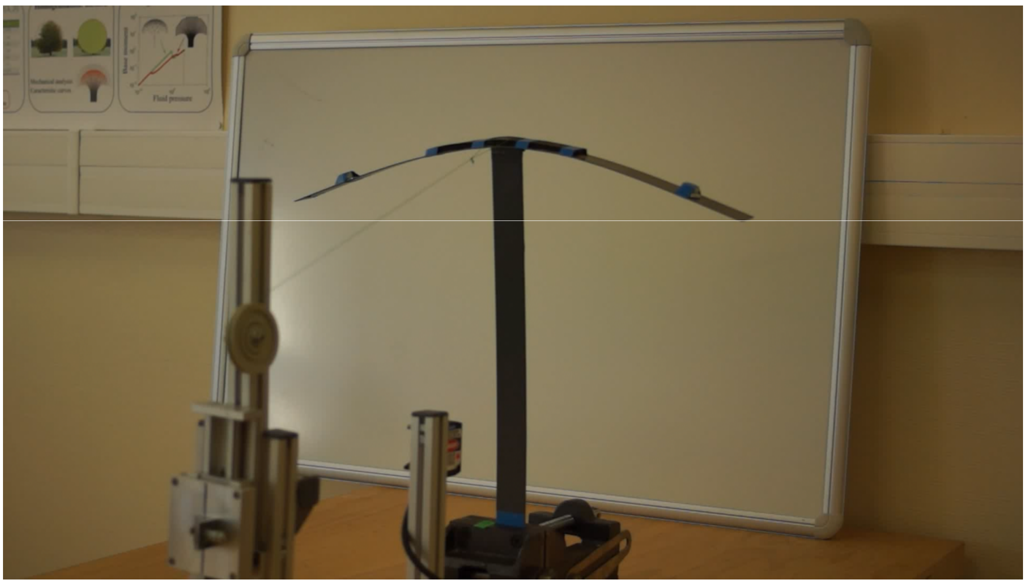
Trunk mode



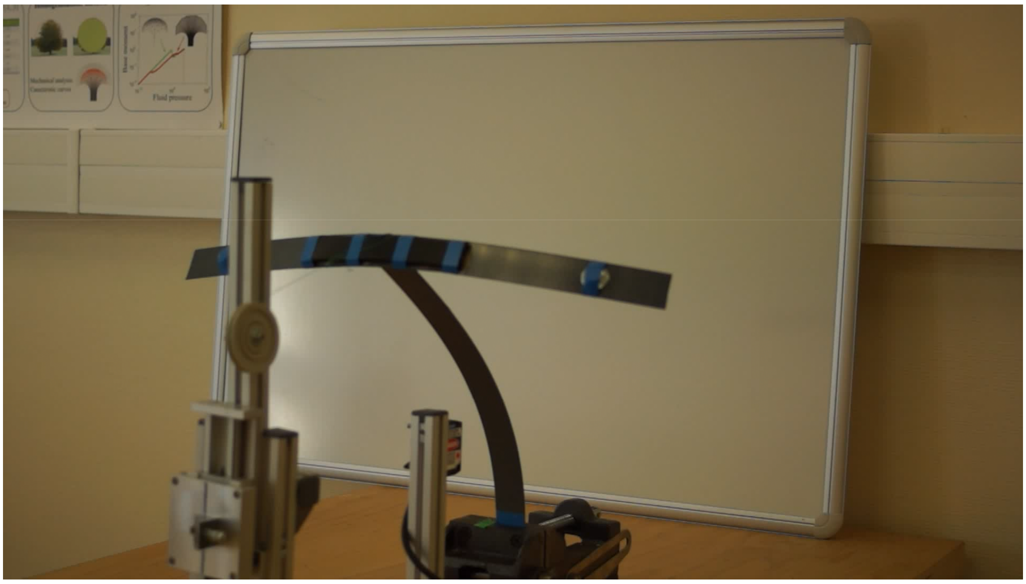
Branches mode

Experimental setup

Low amplitude

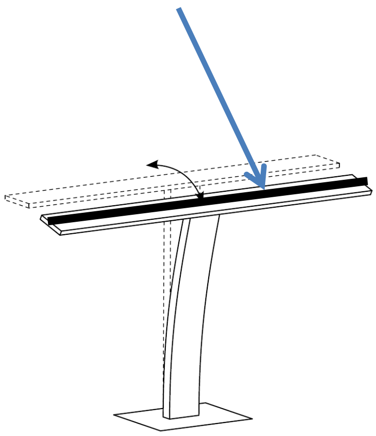


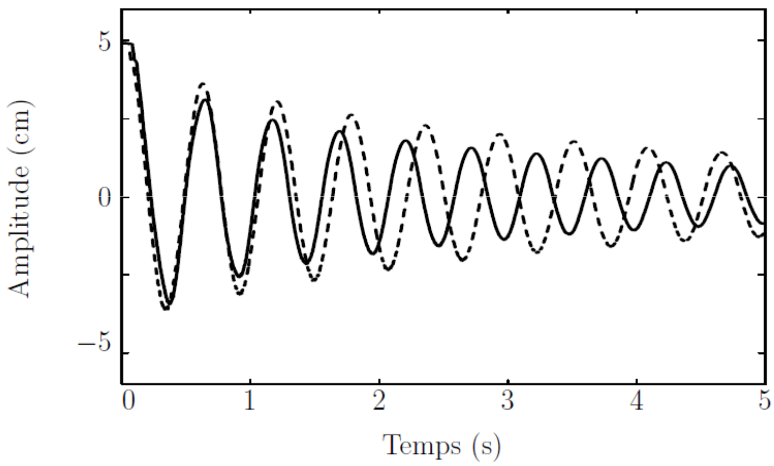
Large amplitude



Free/locked branches comparison

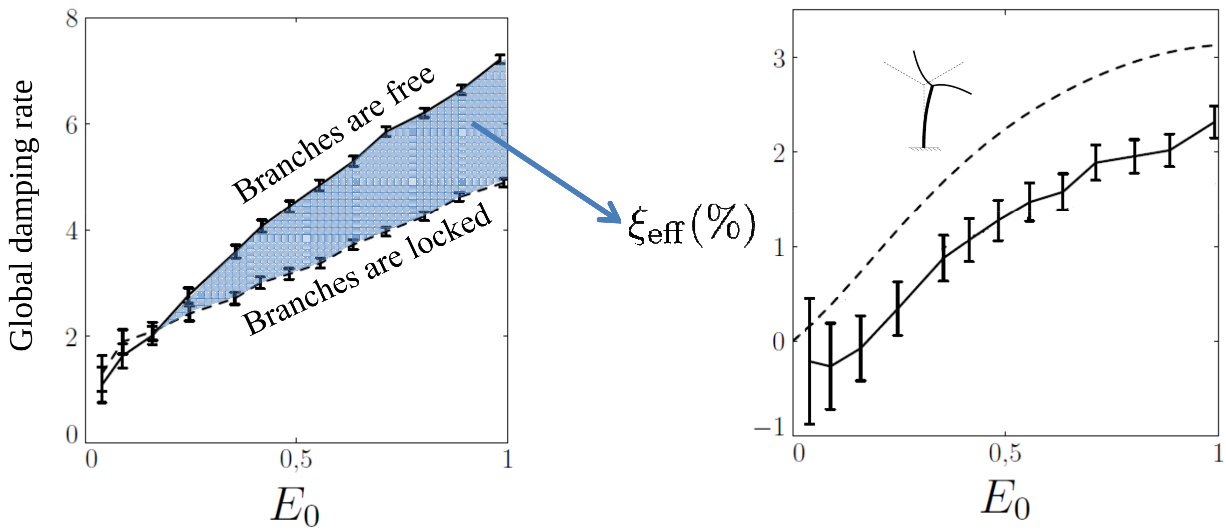
Rigid stick to lock branches





Free branches case is the continuous curve while the locked case (less damped) is the dotted curve.

Amortissement total

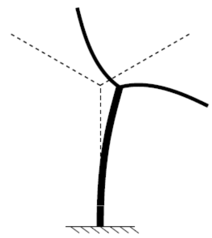


Conclusion

Continous branched structures

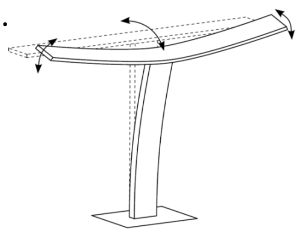
Beam model:

- A more complex modal dynamics.
- Yet, damping by branching brings 3% additionnal damping rate.



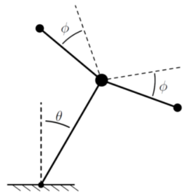
Illustrative experiment:

- Complex damping mecanisms (aerodynamics, etc.).
- Comparison method to identify damping by branching.
- 2% additionnal damping rate from damping by branching.



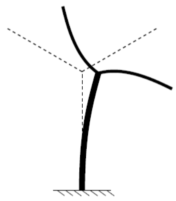
Plan

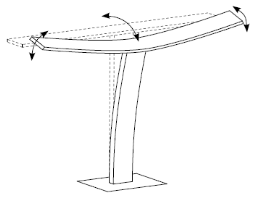
I – Elementary branched model



II – Robustness

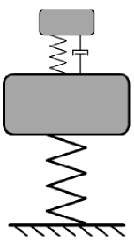
III – Continuous branched structures

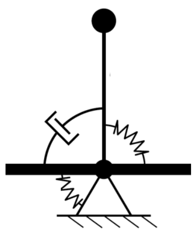




IV – Two proposals of application

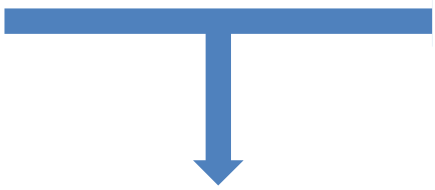
First application

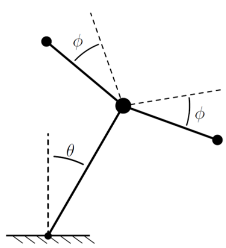




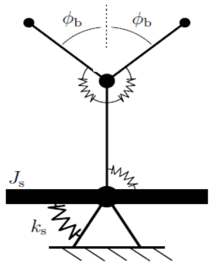
Rotationnal TMD

Coupling fonctions



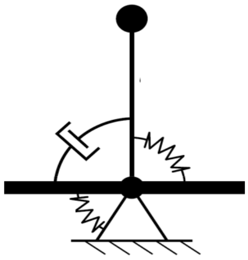


Damping by branching

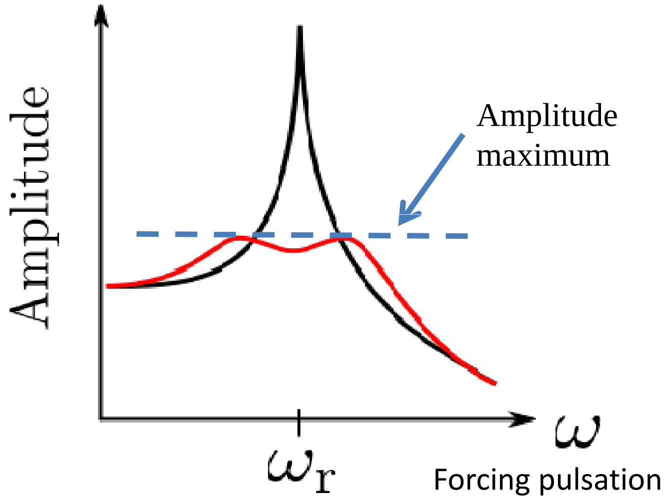


'Tuned-Mass-Branched-Damper'

Comparison with the TMD

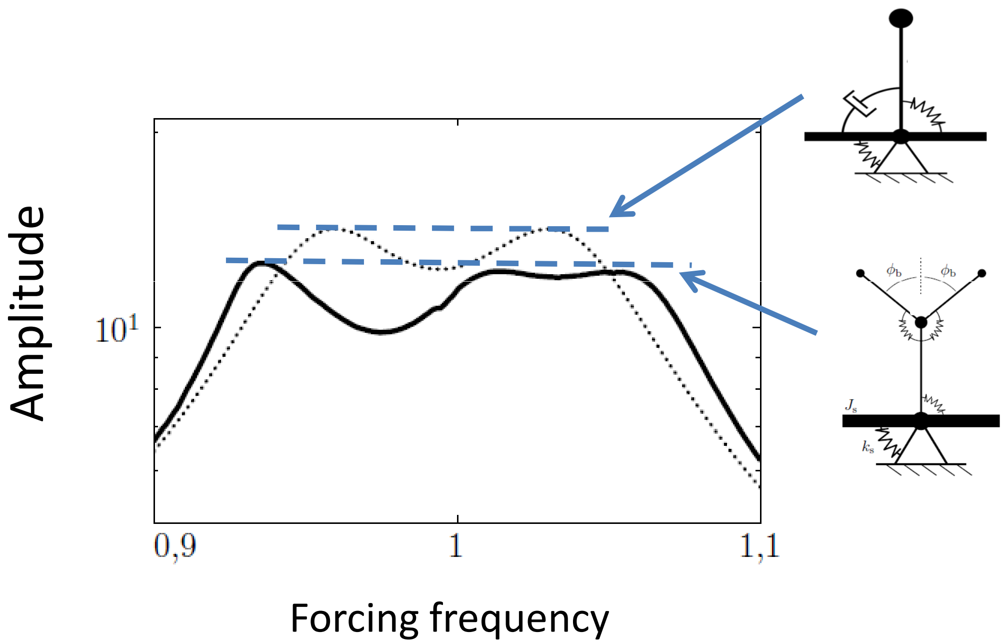


TMD parameters are optimal

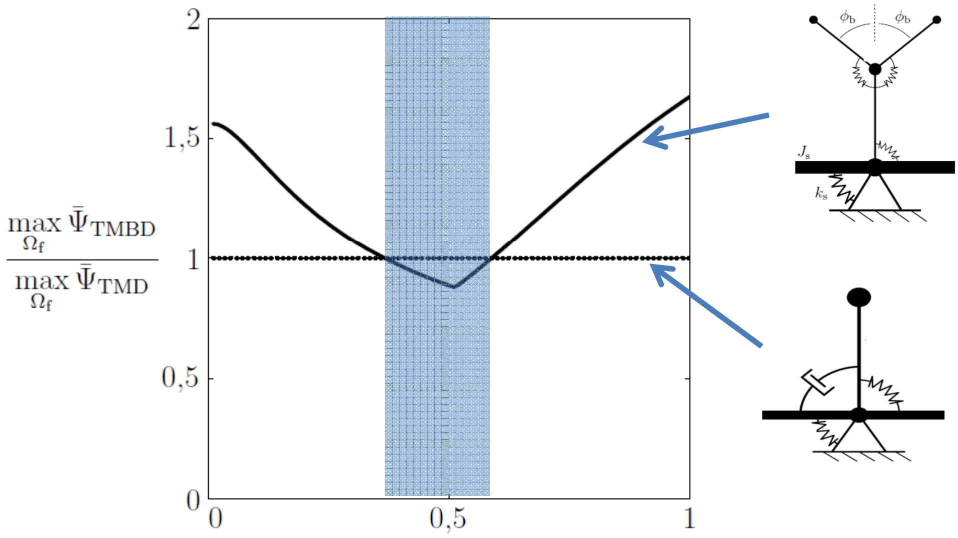


The TMD performance is given by the maximal amplitude of the forced structure

Comparison with the TMD



TMBD is better than TMD only on a small range of parameters



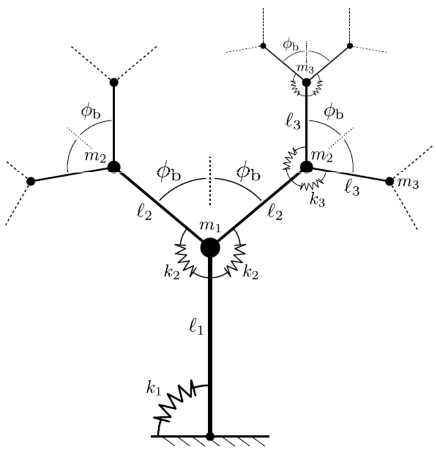
Second application

Ramified structures

Artistic project at Nantes - France

Man-made structures

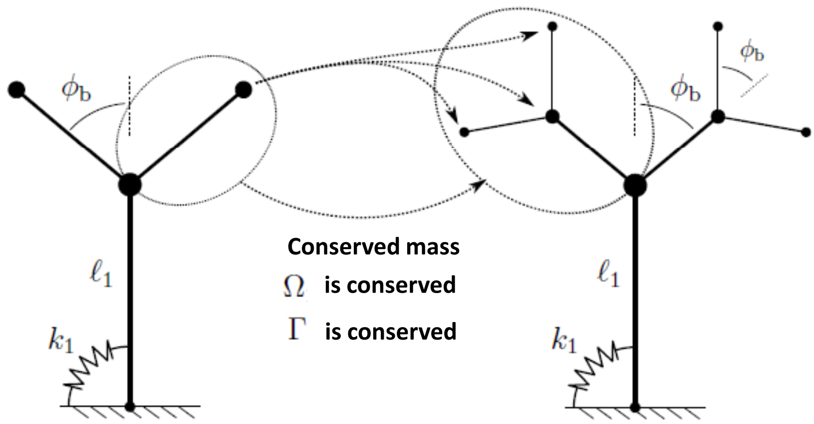
Trees



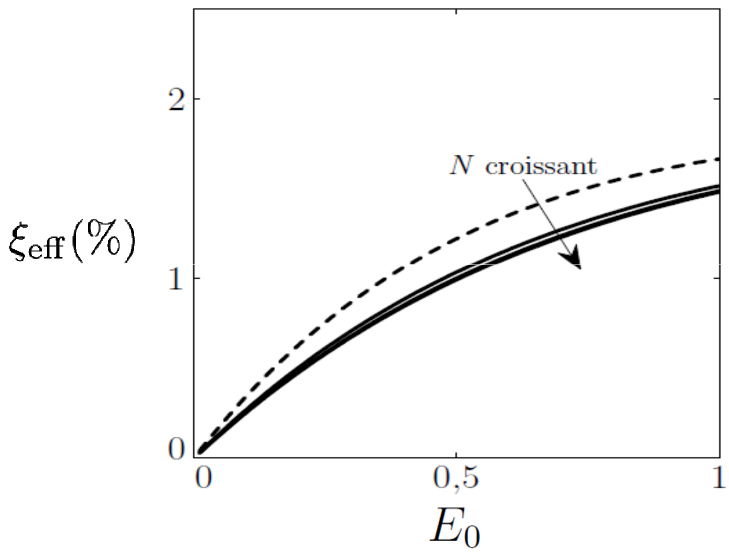
Idealised ramified model

Ramification effects

Criterion: ramification with the same mass

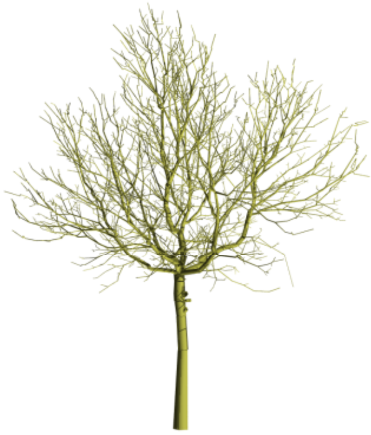


Ramification effects



Damping by branching is not higher in equivalent ramified structures, still it converges toward slighly lower values.

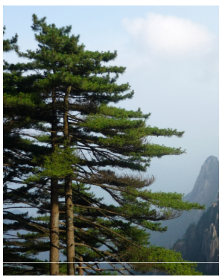
Unequal modal distribution



Arbres	Coefficients allométriques		Rapports équivalents		Fréquences extrapolées			
	β	λ	δ	γ	Ω_1	Ω_2	Ω_3	Ω_4
Noyer commun *Juglans regia*	1,37	0,25	0,50	0,60	**1,38**	3,78	10,40	28,63
Chêne rouge d'Amérique *Quercus rubra*	1,51	0,41	0,64	0,74	**1,16**	**2,08**	3,76	6,79
Chêne blanc d'Amérique *Quercus alba*	1,41	0,28	0,53	0,64	**1,30**	3,22	7,94	19,58
Chêne blanc d'Amérique *Quercus alba*	1,66	0,29	0,54	0,69	**1,13**	**2,39**	5,04	10,63
Peuplier faux-tremble *Populus tremuloides*	1,5	0,29	0,54	0,66	**1,23**	**2,80**	6,40	14,61
Cerisier de Pennsylvanie *Prunus pensylvanica*	1,5	0,24	0,49	0,62	**1,27**	3,28	8,50	22,02
Pin blanc d'Amérique *Pinus strobus*	1,37	0,24	0,49	0,59	**1,39**	3,93	11,15	31,60

→ Only first branches modes are important for damping by branching

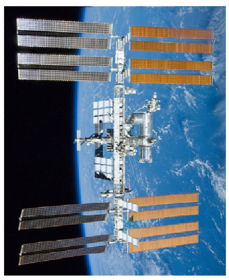
Conclusion



A tree-inspired **damping** mecanism. It is **robust** and specific to damp **large amplitude** motions.

- Elementary branched model
- Robustness
- Beam model & Experiment
- Two application ideas

Multiple ways of application for man-made flexible structures



Perspectives

Arbres

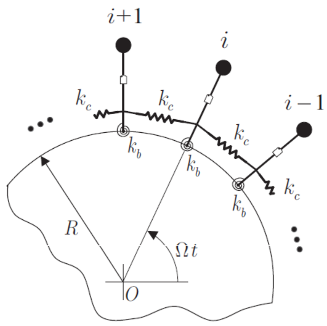
RUDNICKI, 2008

Impact non-linearities ?

Dynamical fluid-structure interaction ?

Perspectives

Ingénierie



OLSON, SHAW & PIERRE, 2005

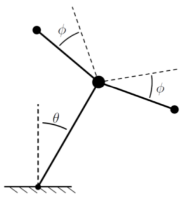
Non-linear rotationnal dampers ?

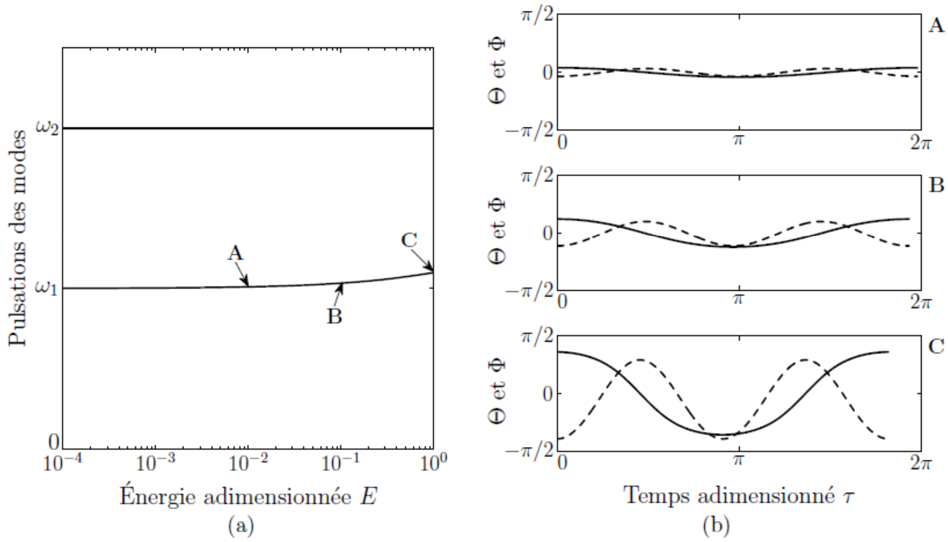
'Stockbridge dampers' evolution ?

MARKIEWICZ & AL, 1995

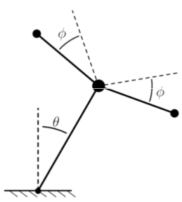
Thank you

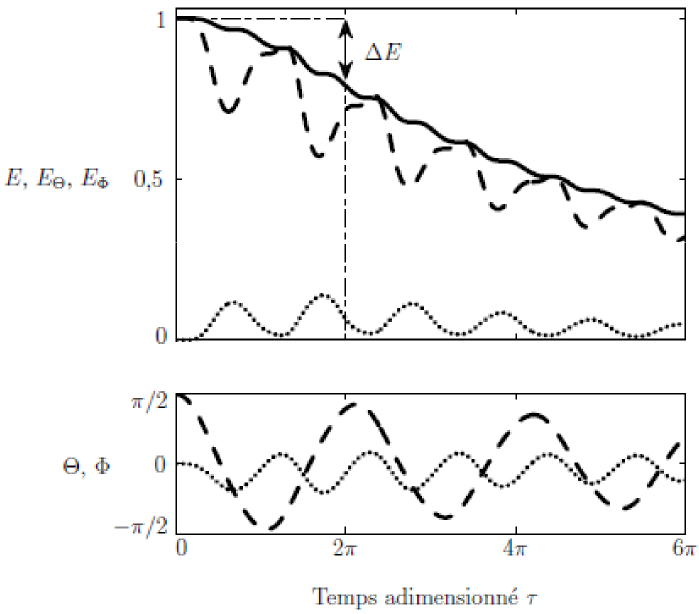
Modes non-linéaires



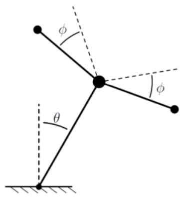


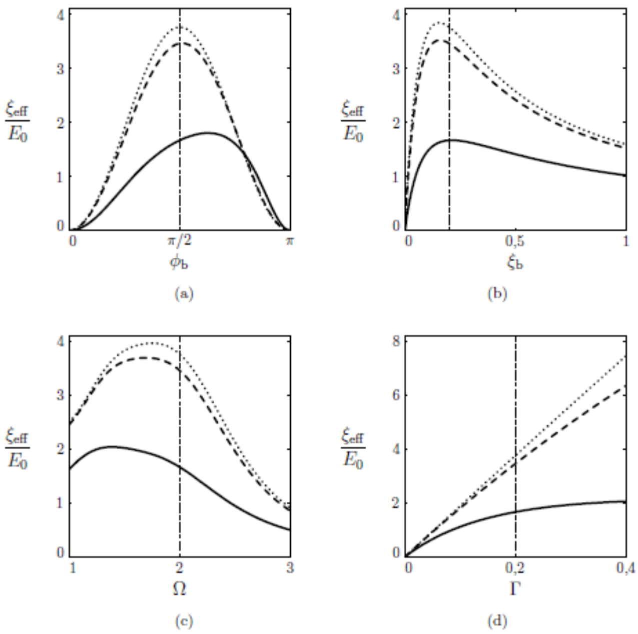
Définition du taux d'amortissement



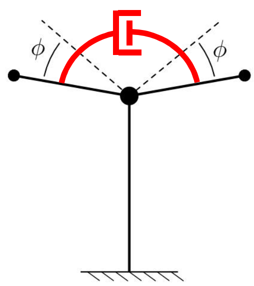


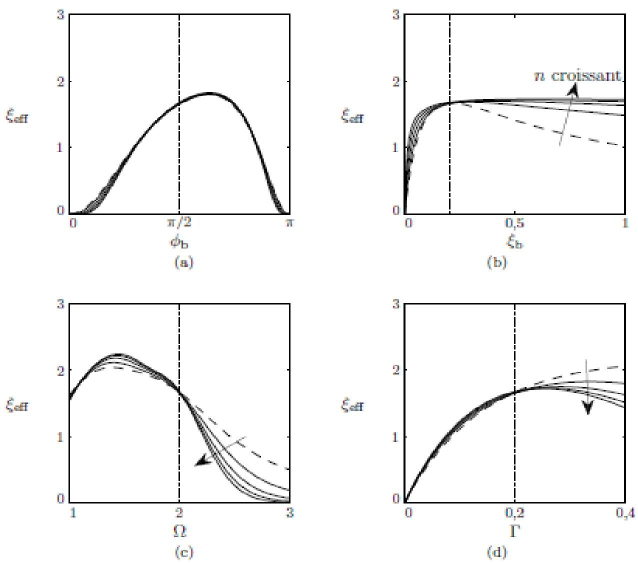
Dépendance paramétrique





Dépendance paramétrique

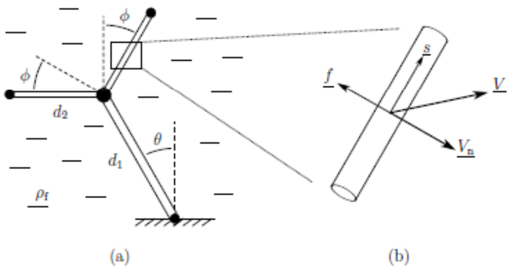


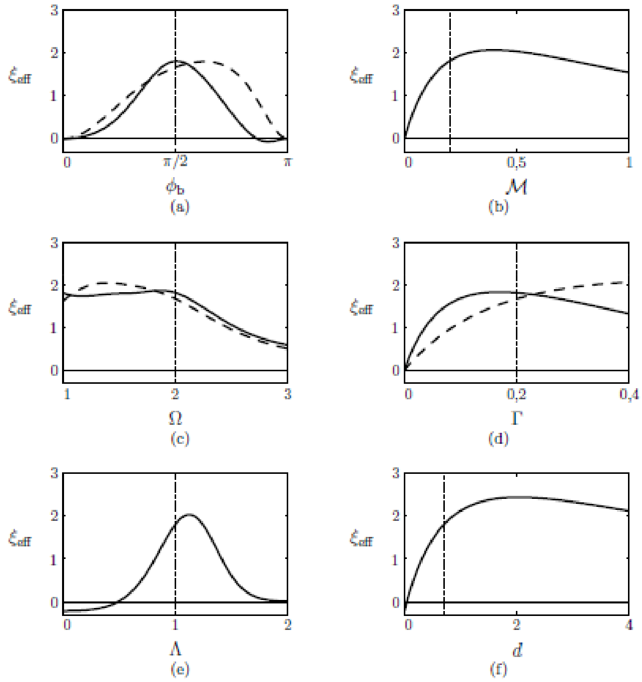


$$\ddot{\Theta} + \Theta = 2\Gamma \left[\dot{\Theta}\, \dot{\Phi}\, \sin(\phi_b + \Phi) - \ddot{\Theta}\big(\cos(\phi_b + \Phi) - \cos\phi_b\big) \right],$$

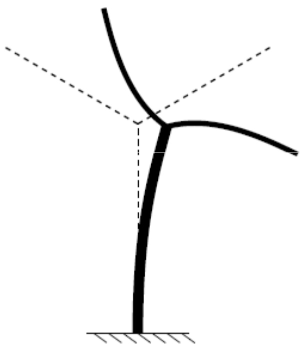
$$\ddot{\Phi} + 2\Omega\xi_b\, \dot{\Phi}|\dot{\Phi}|^{n-1} + \Omega^2\, \Phi = -\dot{\Theta}^2\, \sin(\phi_b + \Phi),$$

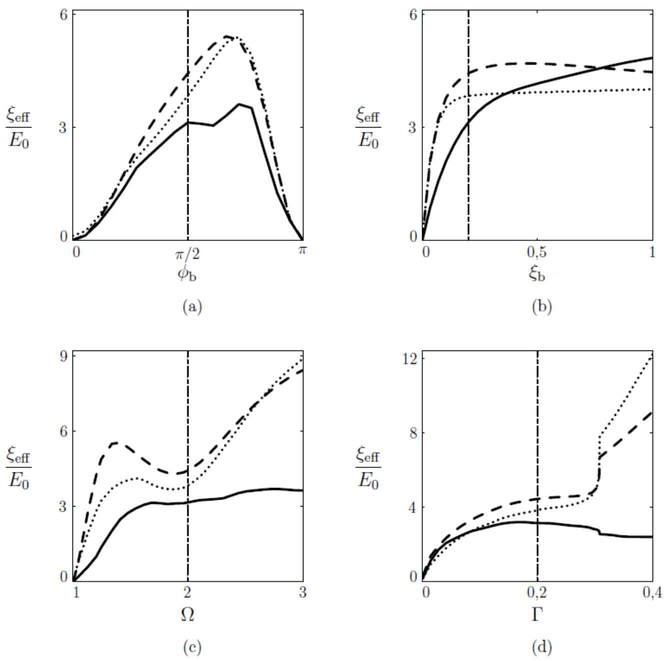
Dépendance paramétrique





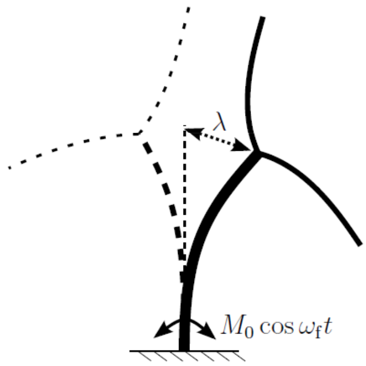
Dépendance paramétrique

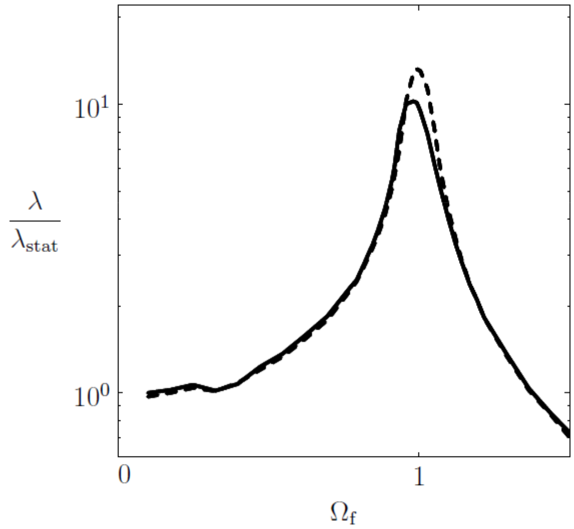




Theckes Benoit

Forçage du modèle continu





Dépendance paramétrique