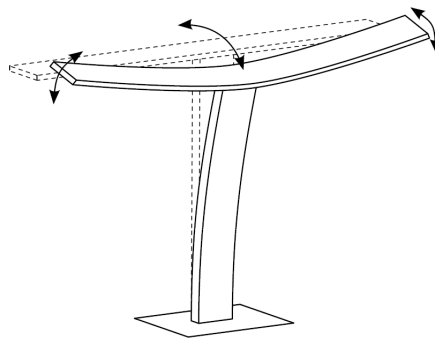


Damping by branching of flexible structure: a bioinspiration from trees



presented by Benoit Theckes



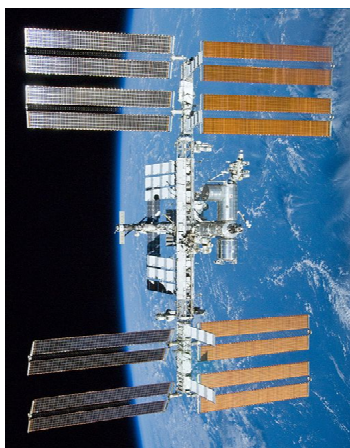
OPÉRATION **MÉCANIQUE** ET **SYSTÈMES VIVANTS**

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



Introduction

Harmful vibrations



ISS

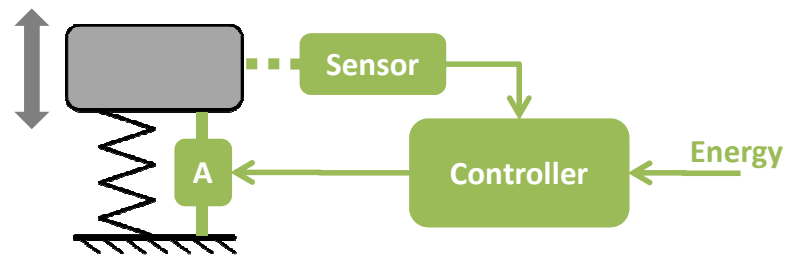


Fonctionnality loss and damage

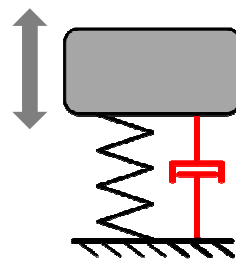
Noise, wear

One solution: damping

- Active means:



- Passive means:

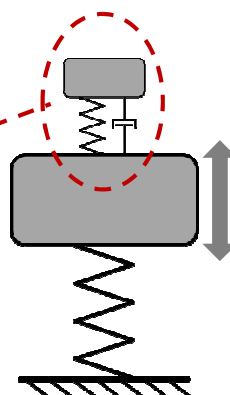


Example of application

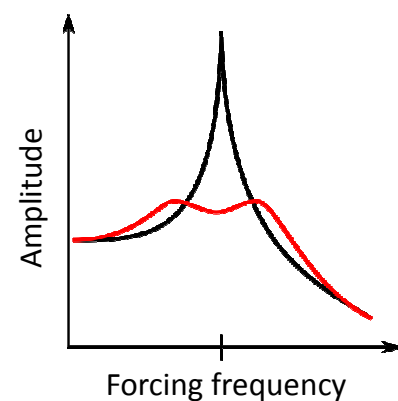
The Tuned-Mass-Damper



Example of application



Principle



Performance

Restriction: damping rate brought by TMD is not amplitude-dependent

Question:

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



Trees

Bioinspired approach



Man-made structures

Damping of large amplitude motions

A matter of survival for trees

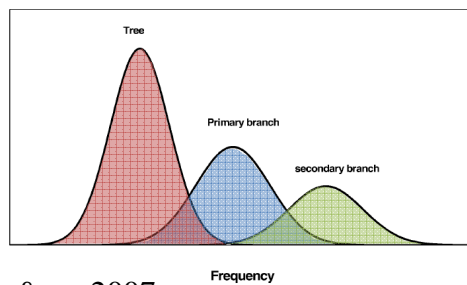
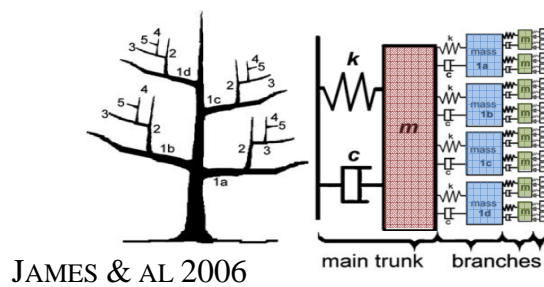


Pull and release test on a Maple tree by KANE

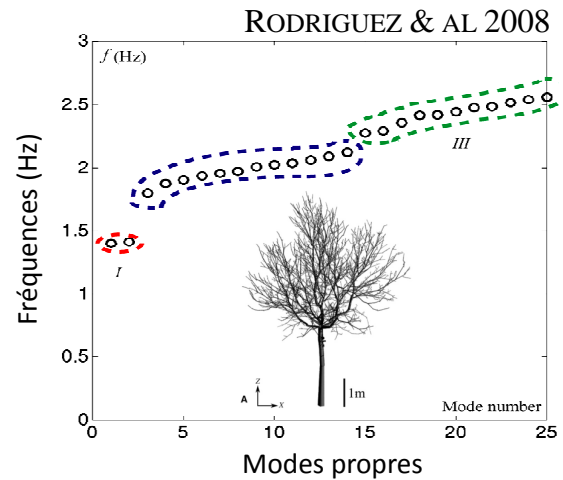
- Wood behavior
- Aerodynamic effects
- ...

Branching role in the linear tree dynamics

- Coupled tree model:



- Modal dynamics:



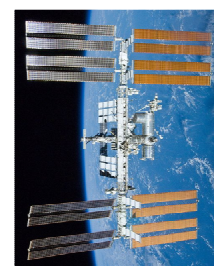
The role of branches in the non-linear dynamics ?

Thesis

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



In trees



In man-made structures

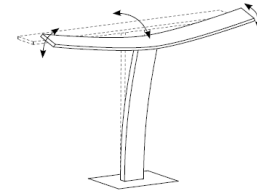
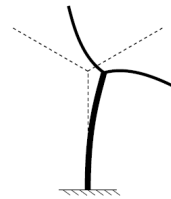
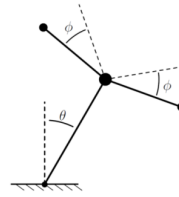
Plan

I – Elementary branched model

II – Robustness

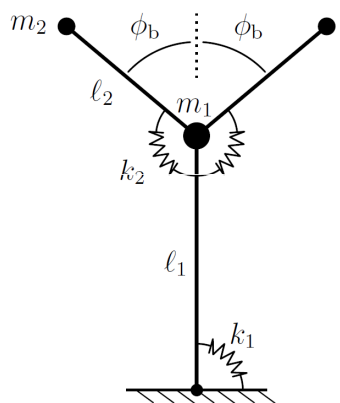
III – Continuous branched structures

IV – Two proposals of application

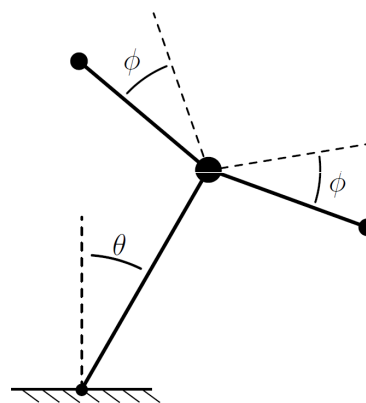


I – Elementary branched model

Elementary branched model

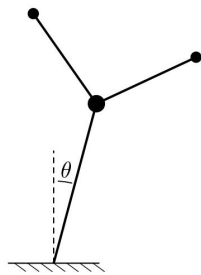


Geometry

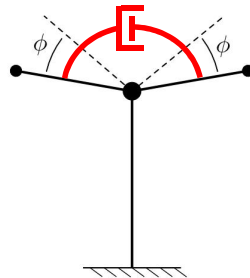


Motion

Equations



Trunk mode



Branches mode

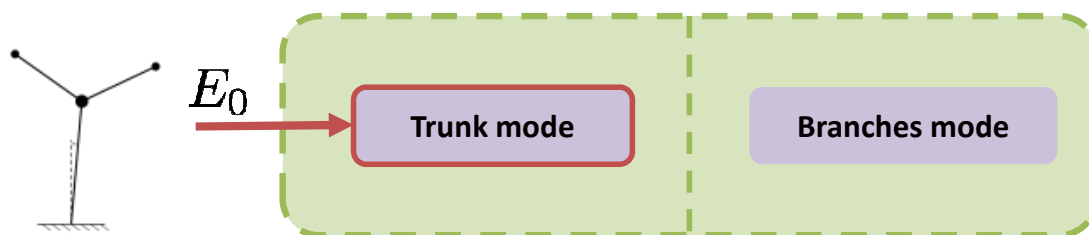
- Frequency ratio $\Omega = \frac{\omega_{\text{Branches}}}{\omega_{\text{Tronc}}}$
- Inertia ratio Γ
- Branching angle ϕ_b
- Damping rate ξ_b

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

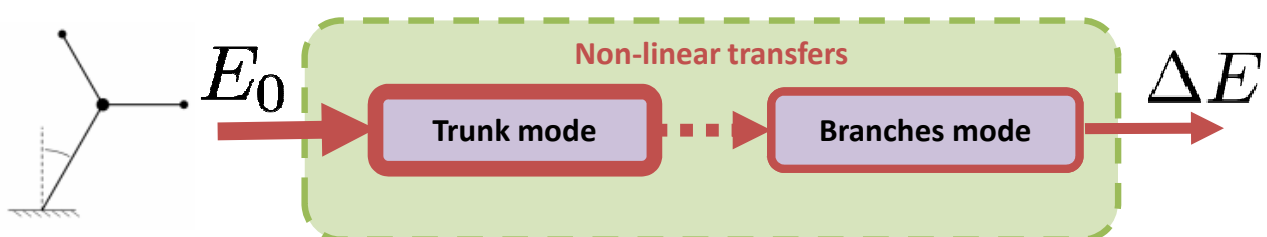
$$\ddot{\Phi} + 2\xi_b \Omega \dot{\Phi} + \Omega^2 \Phi = -\dot{\Theta}^2 \sin(\phi_b + \Phi).$$

Pull and Release on the trunk

- Linear case:

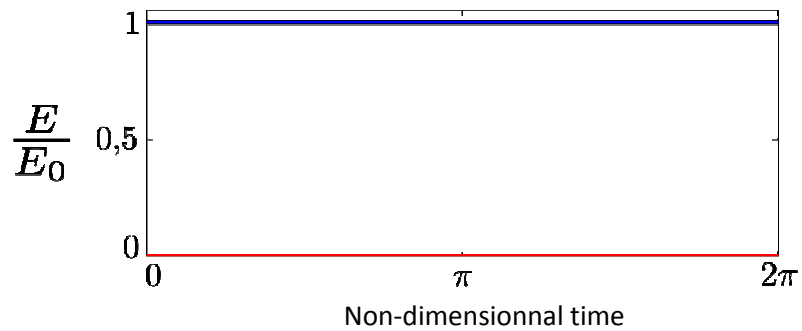


- Non-linear case:

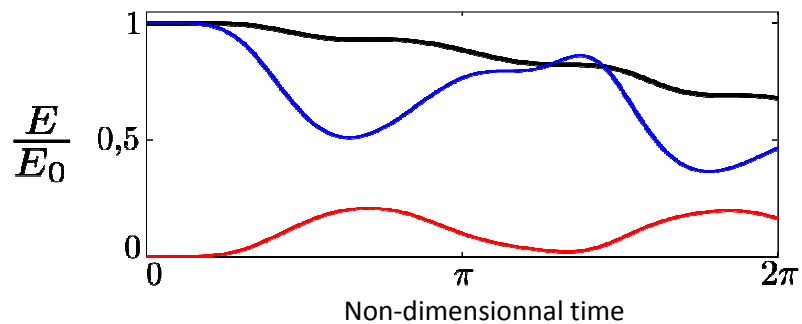


Damping by branching

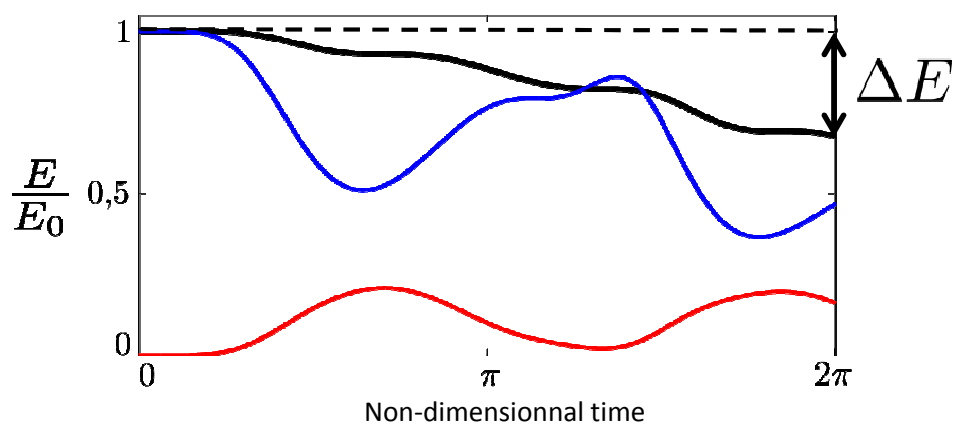
- Linear case:



- Non-linear case:



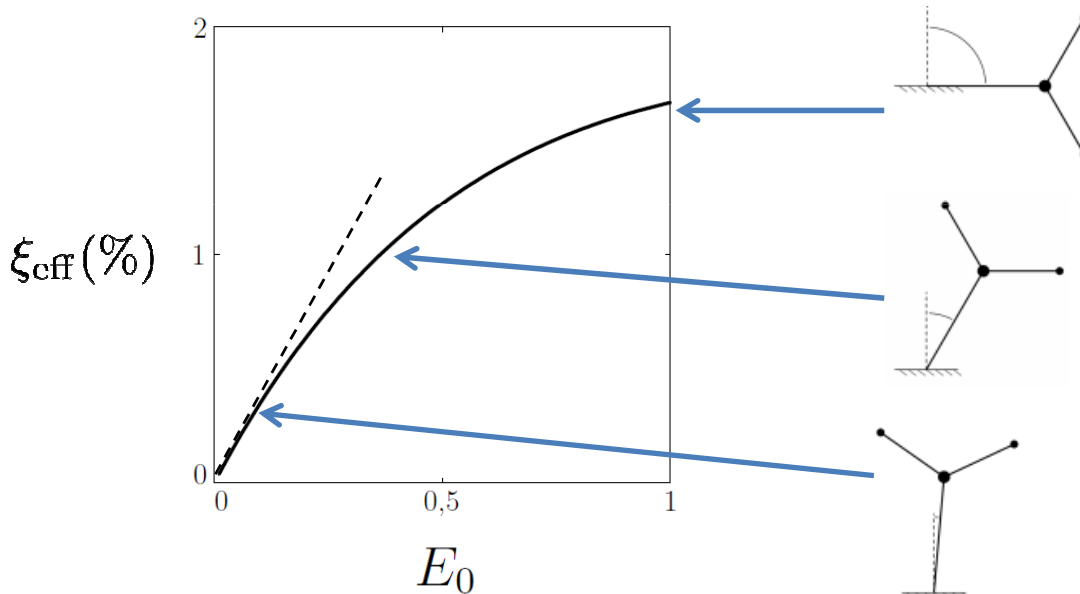
Arbitrary definition



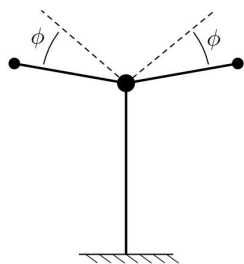
- Defined from the global loss of the total energy in one oscillation of the trunk:

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

Increases with energy



First-order non-linearities



The system of two equations is simplified to:

$$\ddot{\Phi}(t) + \Omega^2 \Phi(t) = E_0 \sin^2 \phi_b \cos 2t$$

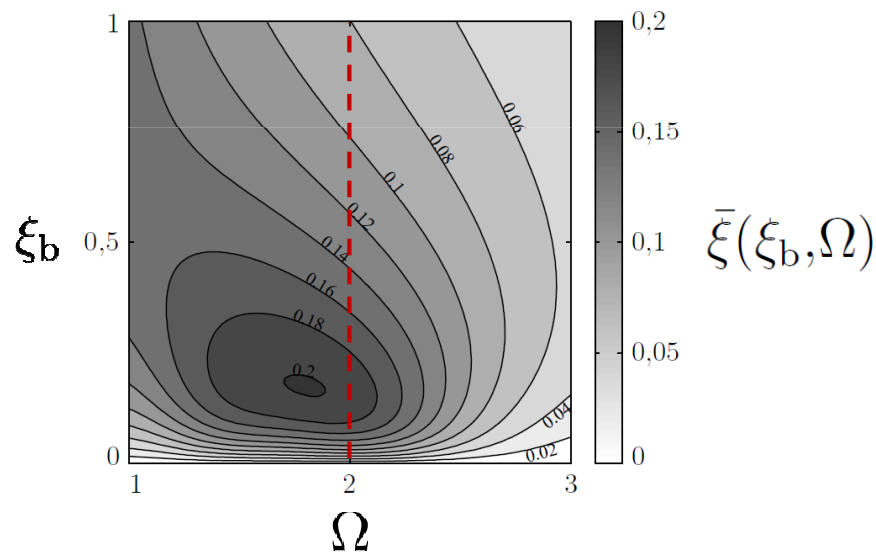


Internal non-linear resonance if $\Omega = 2$

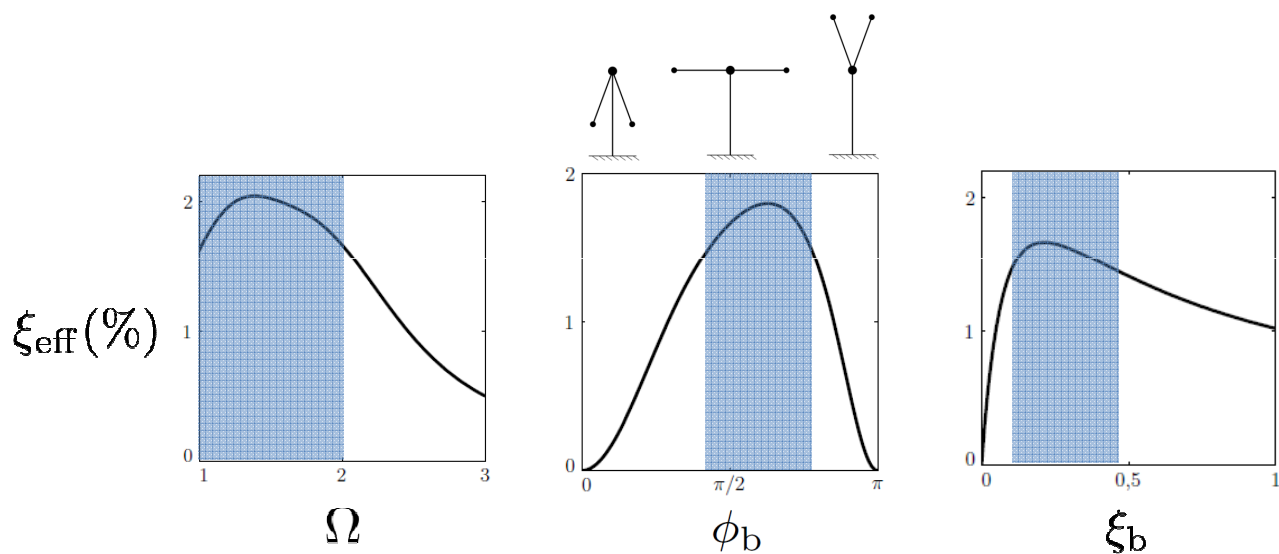
$$\xi_{\text{eff}} = E_0 \Gamma \sin^2 \phi_b \bar{\xi}(\xi_b, \Omega)$$

Analytic results

$$\xi_{\text{eff}} = E_0 \Gamma \sin^2 \phi_b \bar{\xi}(\xi_b, \Omega)$$



Parameters dependency



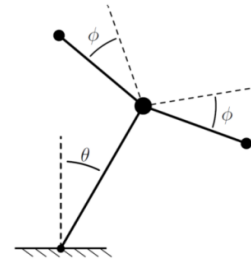
Wide range of optimal values

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.



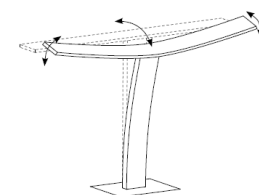
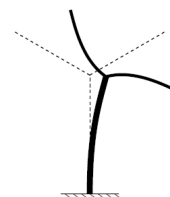
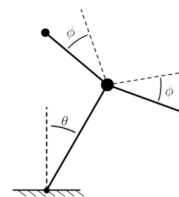
Plan

I – Elementary branched model

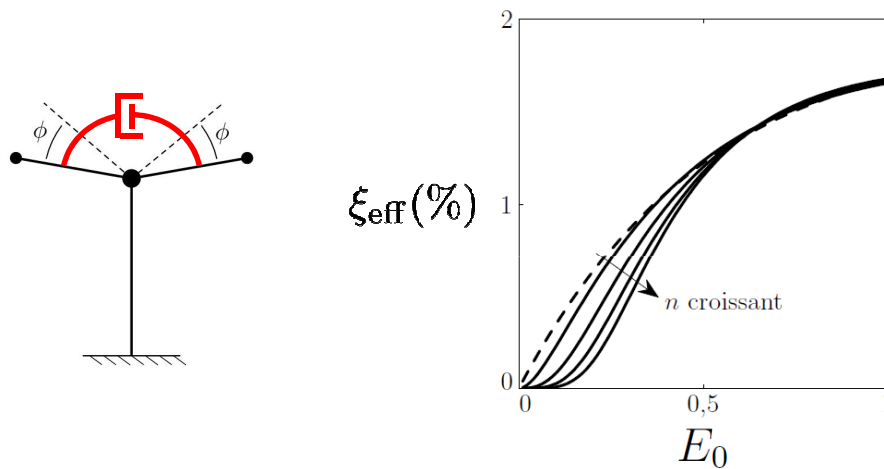
II – Robustness

III – Continuous branched structures

IV – Two proposals of application



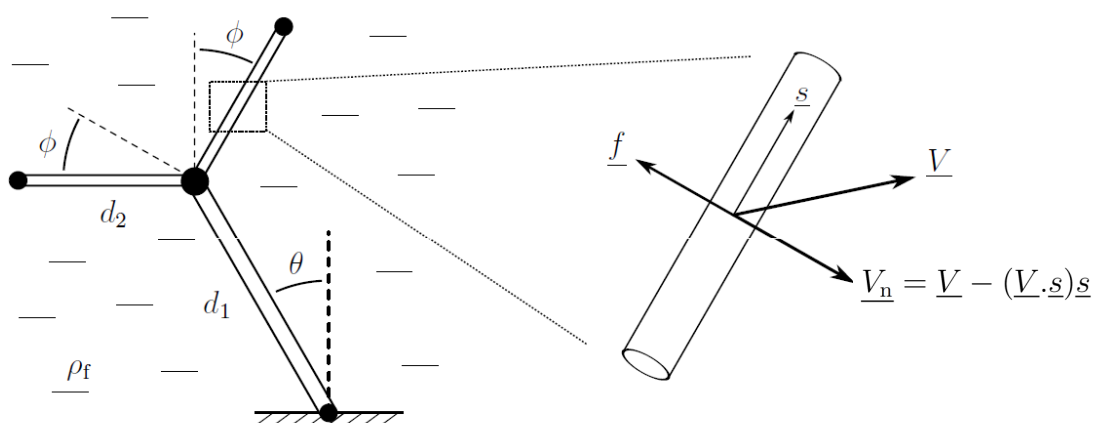
Non-linear damping on the branches mode



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

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

Aerodynamic damping



Oscillations in a fluide at rest

$$\underline{f}_i = -\frac{1}{2} \rho_f C_D d_i |\underline{V}_n| \underline{V}_n$$

Equations

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

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

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

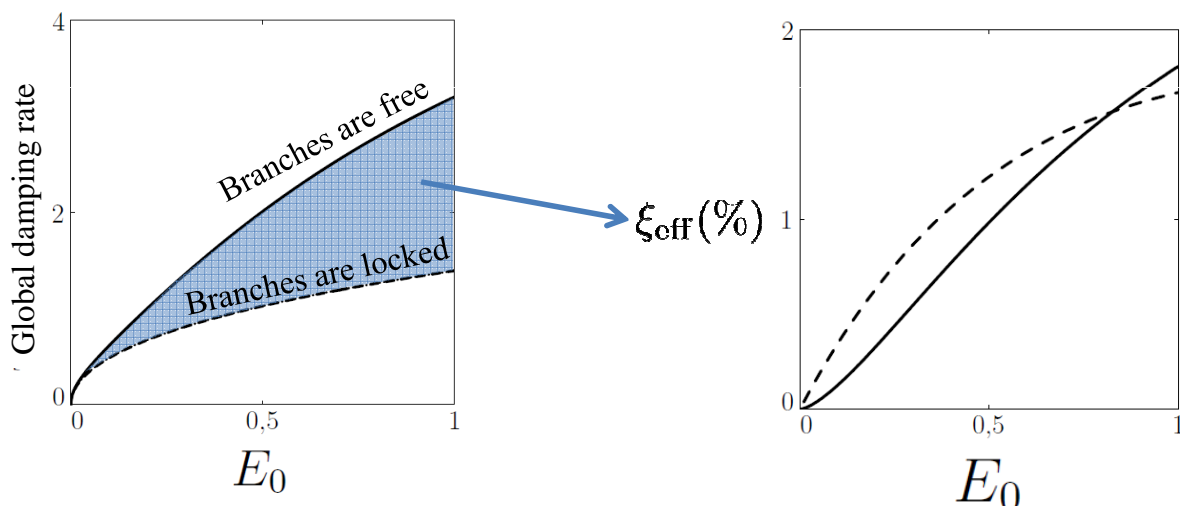
Aerodynamic damping is share on the whole structure: on the branches mode but also on the trunk mode.

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

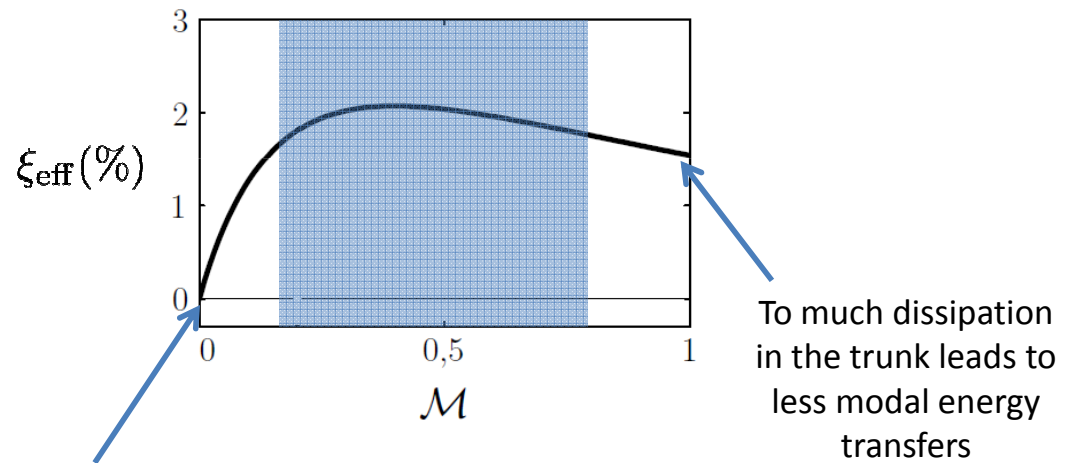
Damping by branching

Comparison between two case:

- Free branches motion
- Locked branches motion



Mass number effect



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

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

Conclusion

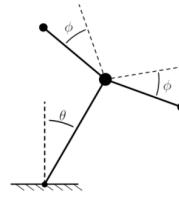
Robustness

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

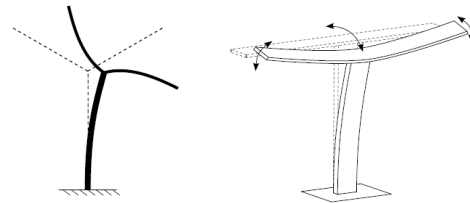
Plan

I – Elementary branched model



II – Robustness

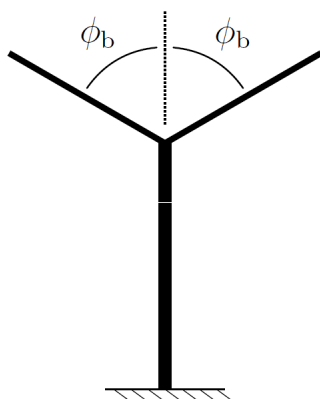
III – Continuous branched structures



IV – Two proposals of application

III – Continuous branched structures

Continuous branched model

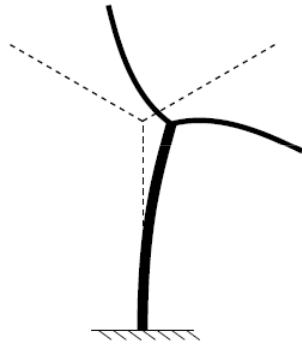


Geometry

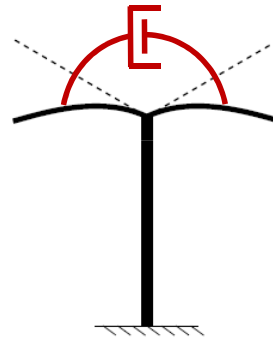
CAST3M software :

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

Modal dynamics

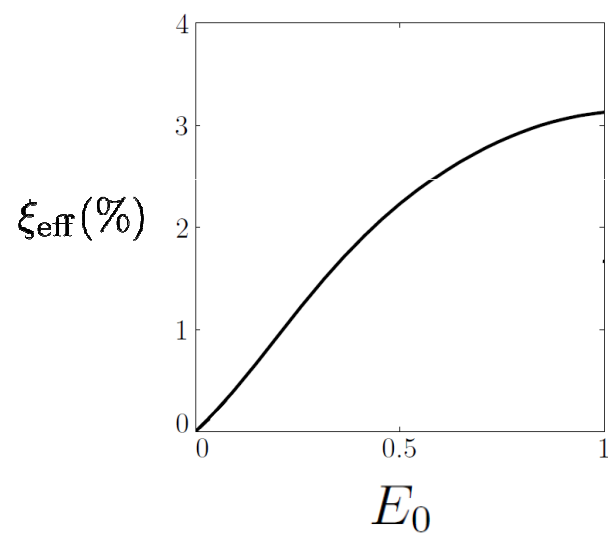
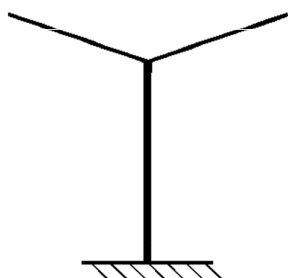


Trunk mode

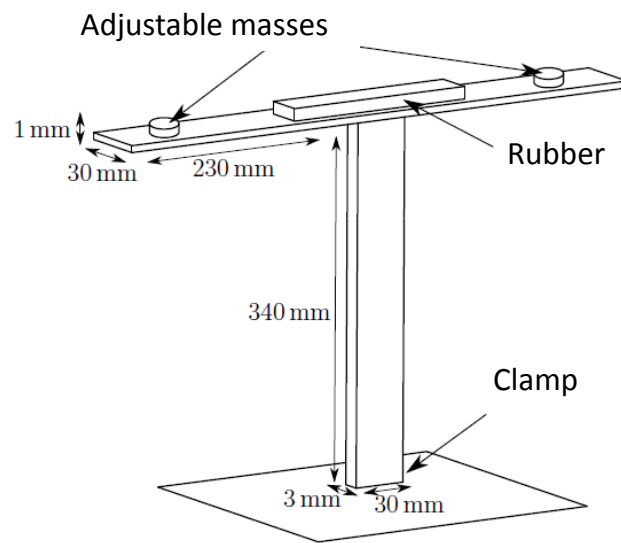


Branches mode

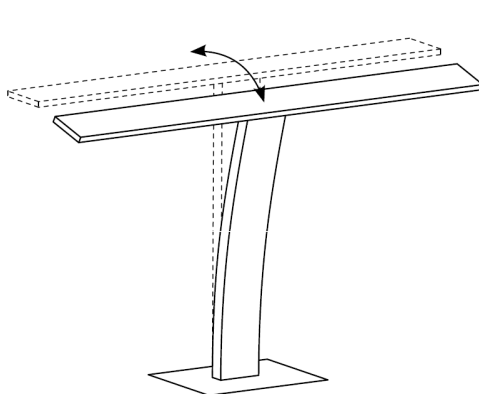
Damping by branching



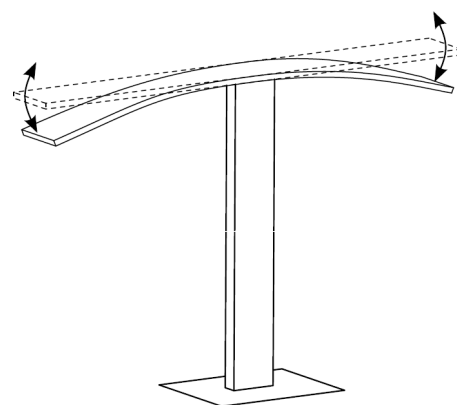
Illustrative experiment



Modal dynamics



Trunk mode

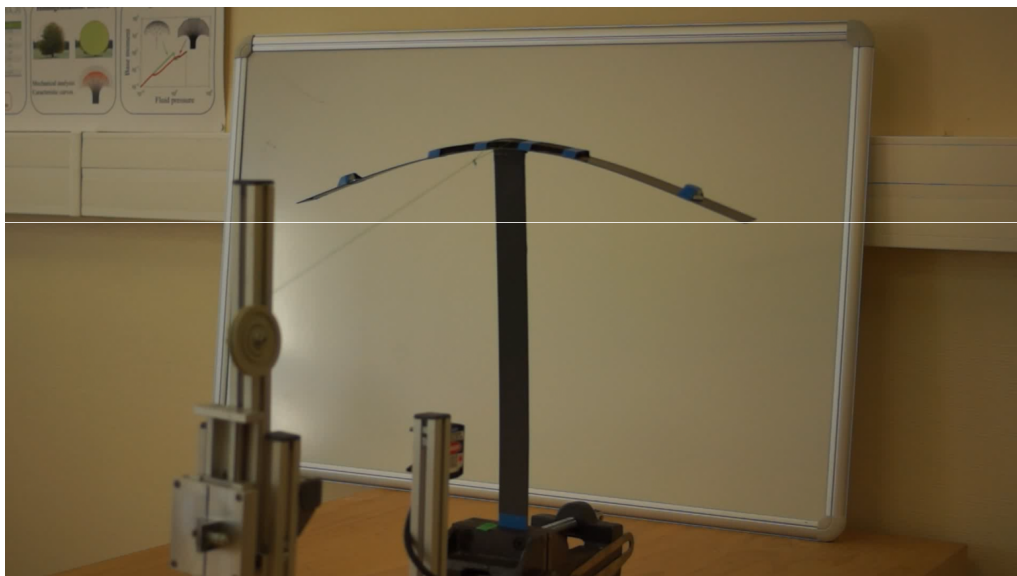


Branches mode

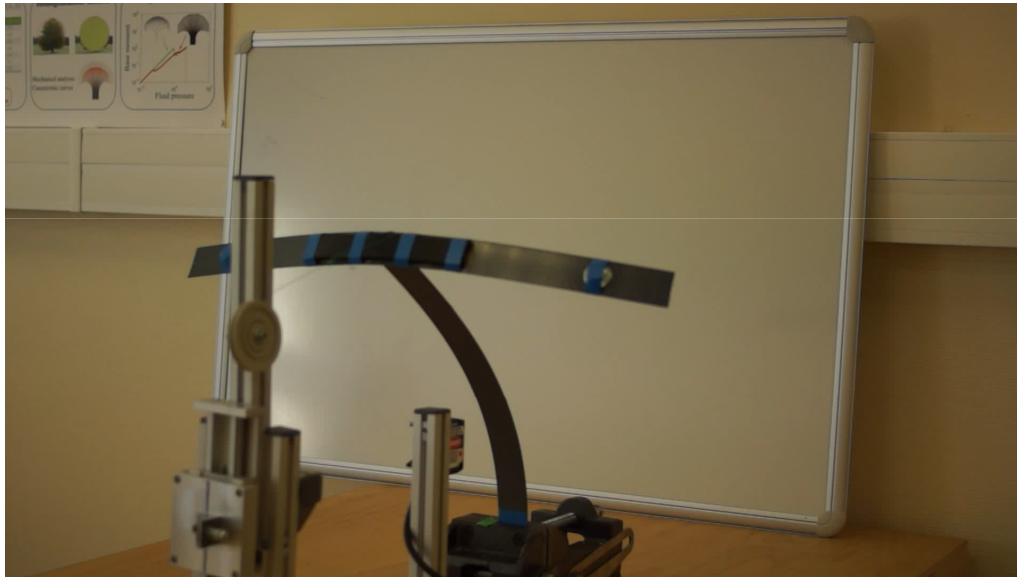
Experimental setup



Low amplitude

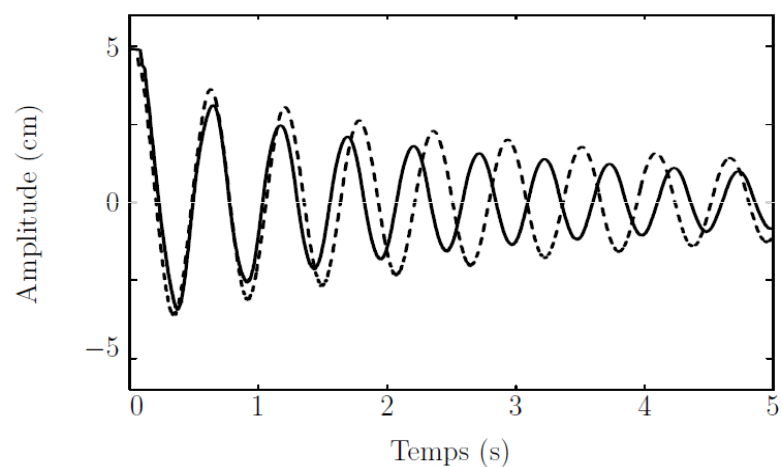
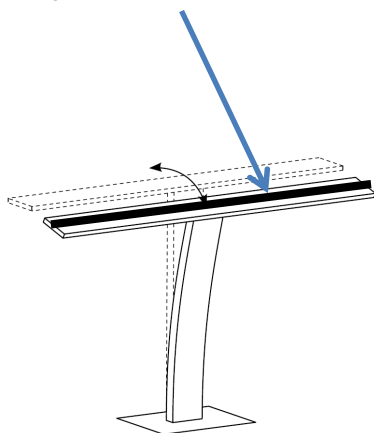


Large amplitude



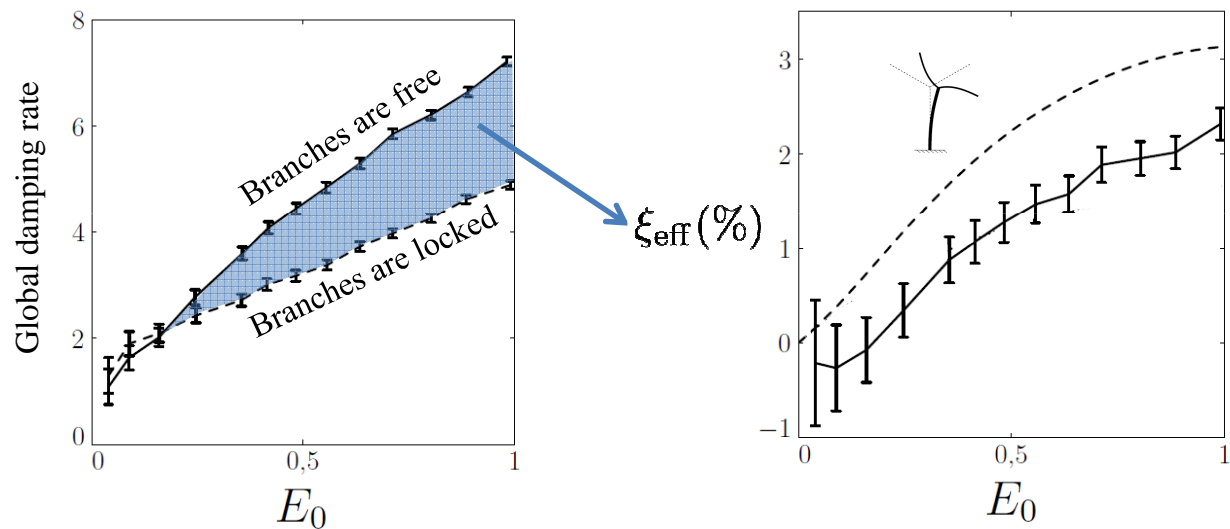
Free/locked branches comparison

Rigid stick to lock branches



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

Amortissement total

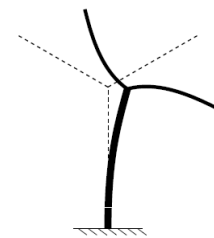


Conclusion

Continuous branched structures

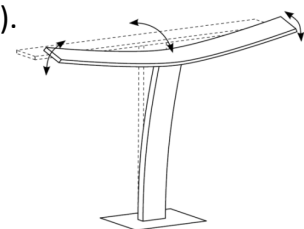
➔ Beam model:

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



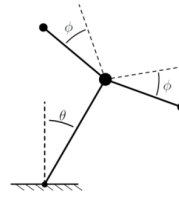
➔ Illustrative experiment:

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

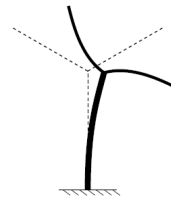


Plan

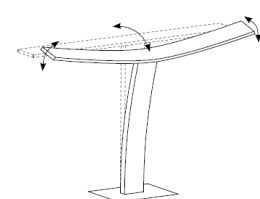
I – Elementary branched model



II – Robustness



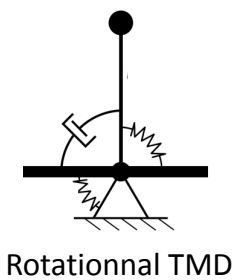
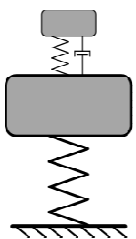
III – Continuous branched structures



IV – Two proposals of application

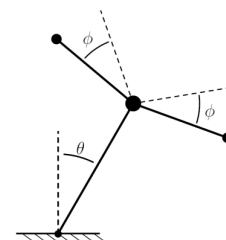
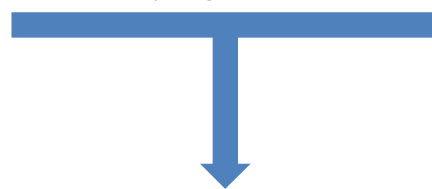
IV – Applications

First application

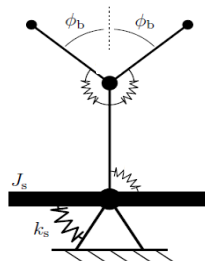


Rotationnal TMD

Coupling functions

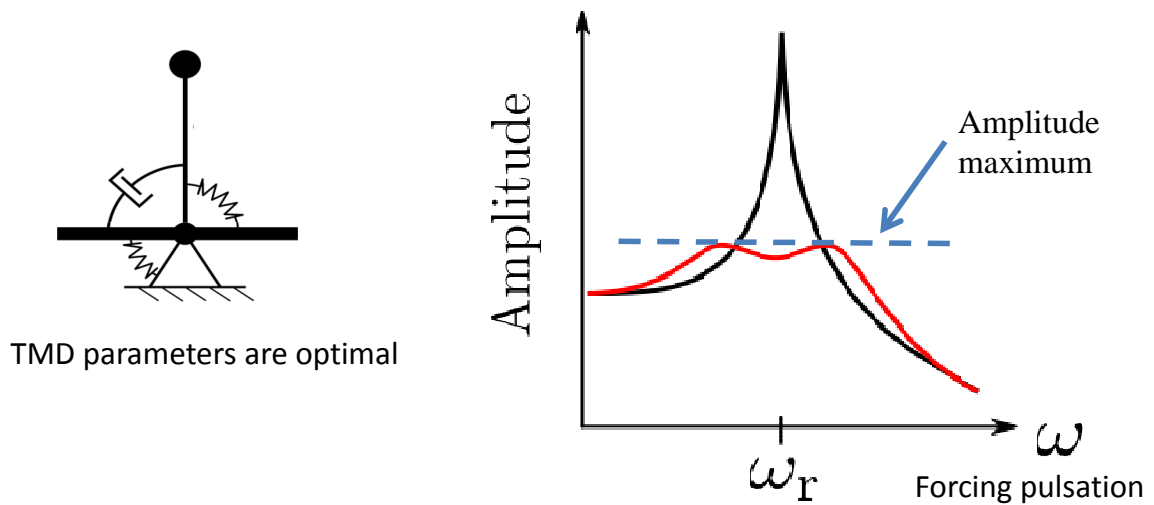


Damping by branching



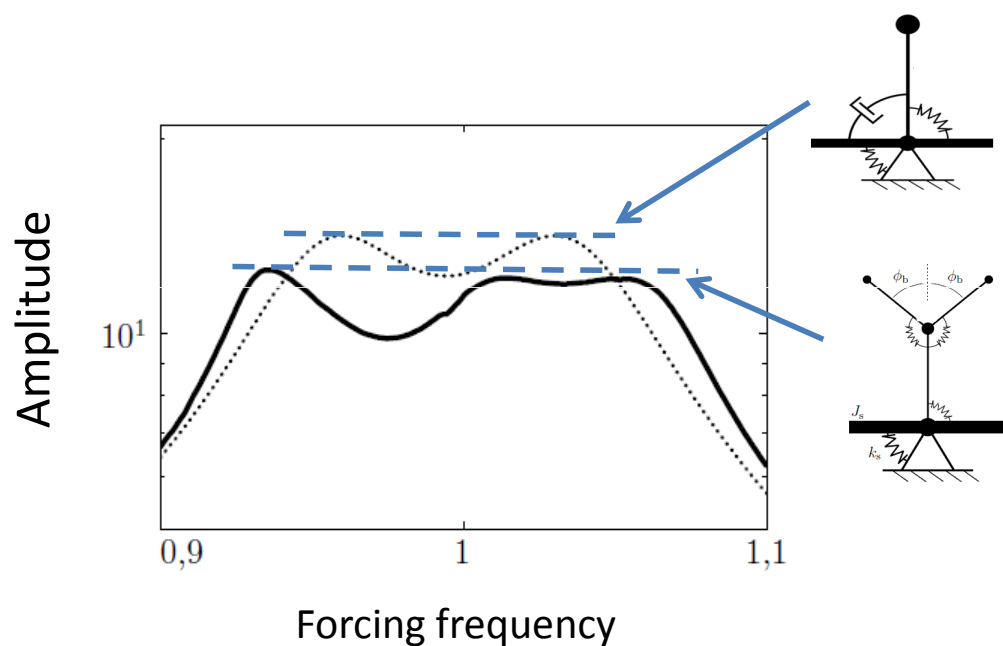
'Tuned-Mass-Branched-Damper'

Comparison with the TMD

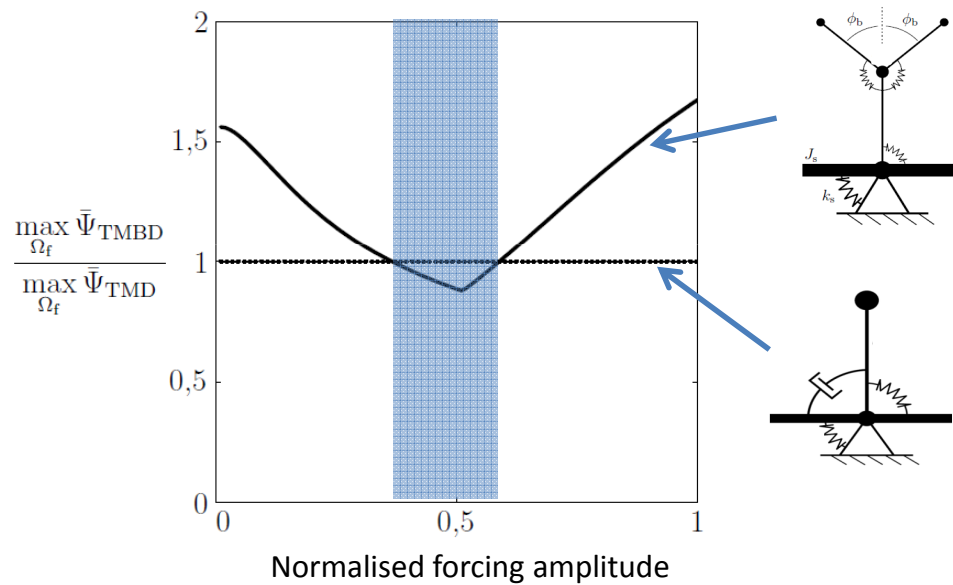


The TMD performance is given by the maximal amplitude of the forced structure

Comparison with the TMD



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



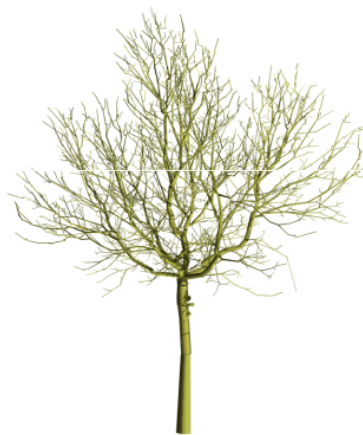
Second application

Ramified structures

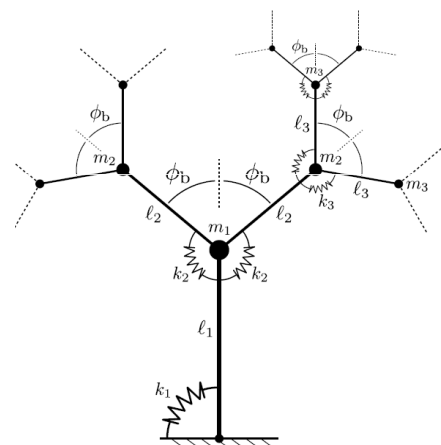


Artistic project at Nantes - France

Man-made structures



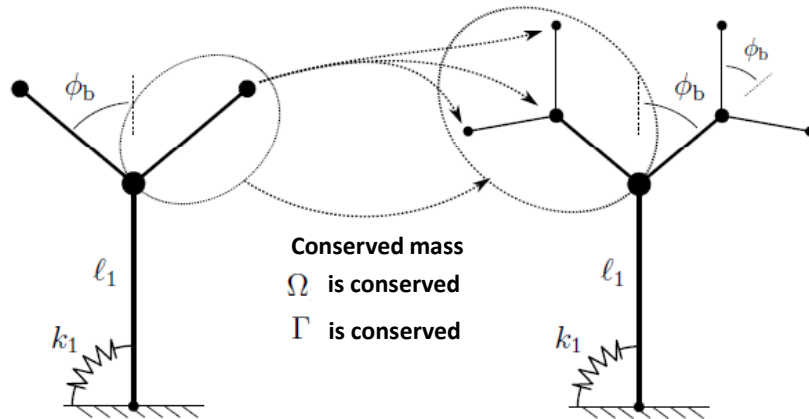
Trees



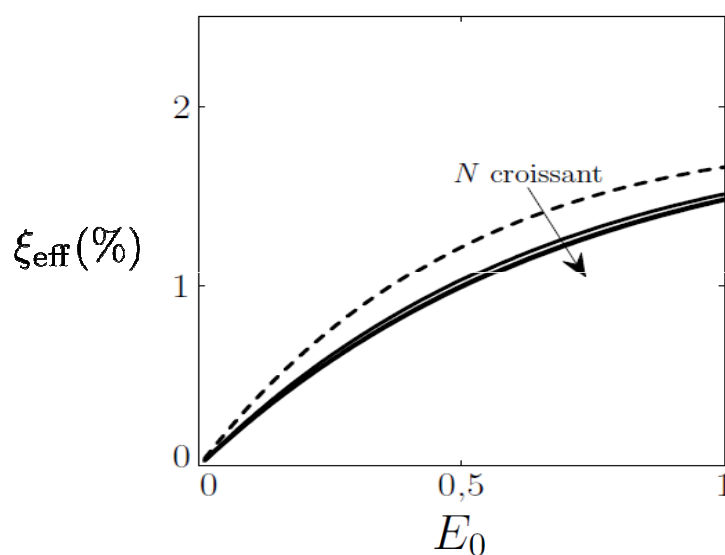
Idealised ramified model

Ramification effects

Criterion: ramification with the same mass

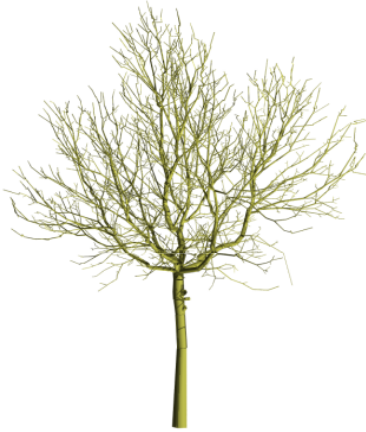


Ramification effects



➔ Damping by branching is not higher in equivalent ramified structures, still it converges toward slightly 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 <i>Juglans regia</i>	1,37	0,25	0,50	0,60	1,38	3,78	10,40	28,63
Chêne rouge d'Amérique <i>Quercus rubra</i>	1,51	0,41	0,64	0,74	1,16	2,08	3,76	6,79
Chêne blanc d'Amérique <i>Quercus alba</i>	1,41	0,28	0,53	0,64	1,30	3,22	7,94	19,58
Chêne blanc d'Amérique <i>Quercus alba</i>	1,66	0,29	0,54	0,69	1,13	2,39	5,04	10,63
Peuplier faux-tremble <i>Populus tremuloides</i>	1,5	0,29	0,54	0,66	1,23	2,80	6,40	14,61
Cerisier de Pennsylvanie <i>Prunus pennsylvanica</i>	1,5	0,24	0,49	0,62	1,27	3,28	8,50	22,02
Pin blanc d'Amérique <i>Pinus strobus</i>	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

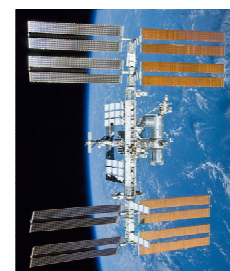


A tree-inspired **damping** mechanism. It is **robust** and specific to damp **large amplitude** motions.



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

Multiple ways of application for man-made flexible structures



Perspectives

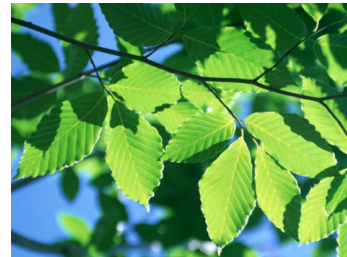
Arbres



RUDNICKI, 2008

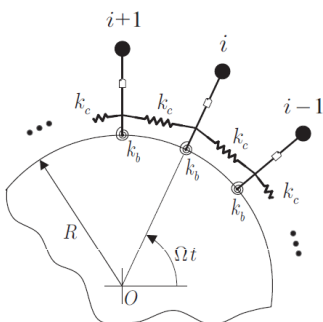
Impact non-linearities ?

Dynamical fluid-structure interaction ?



Perspectives

Ingénierie



OLSON, SHAW & PIERRE, 2005

Non-linear rotationnal dampers ?

'Stockbridge dampers' evolution ?



MARKIEWICZ & AL, 1995



Thank you

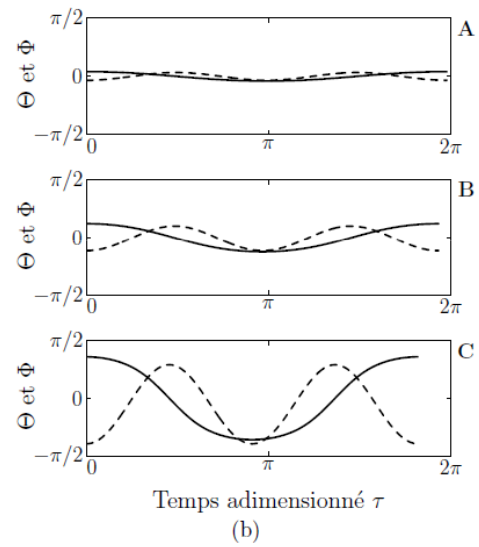
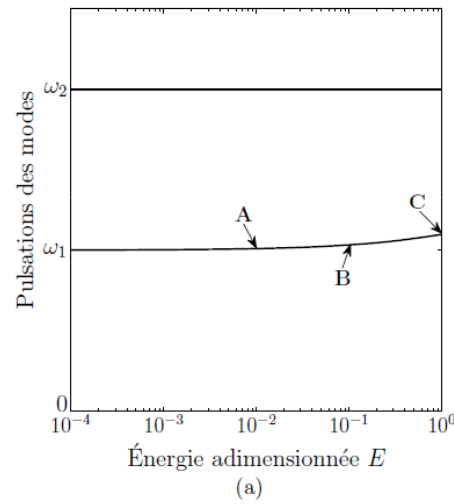
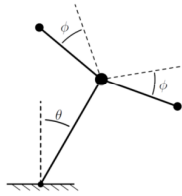
Theckes Benoit



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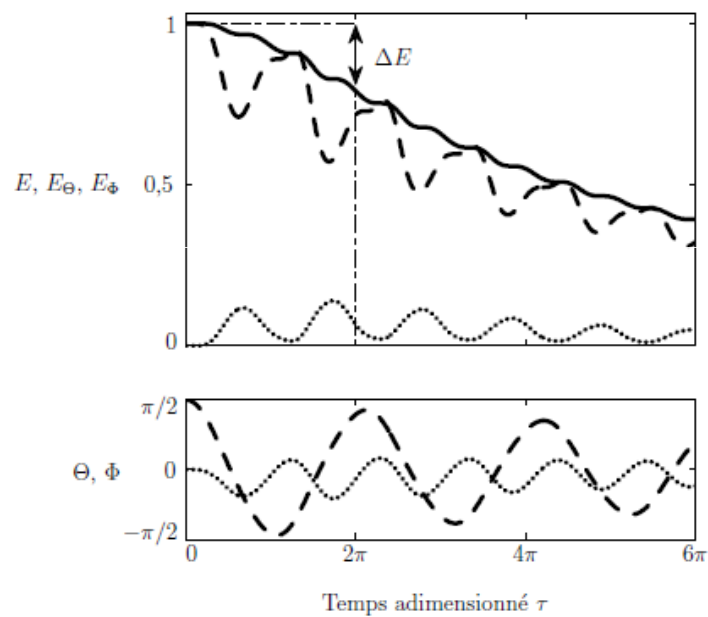
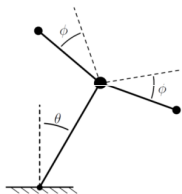


Modes non-linéaires



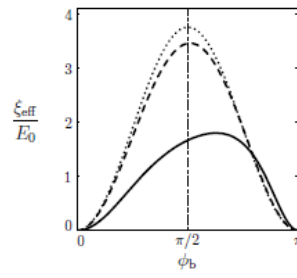
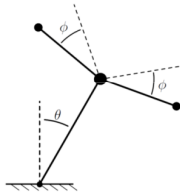
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Définition du taux d'amortissement

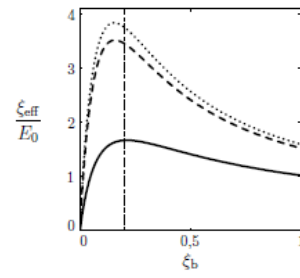


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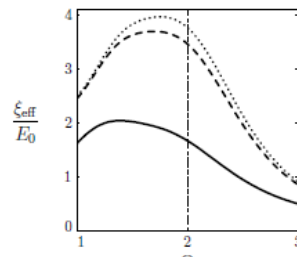
Dépendance paramétrique



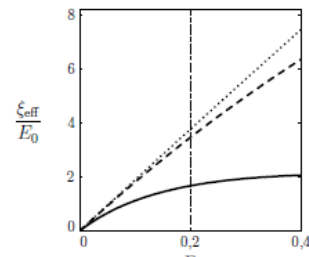
(a)



(b)



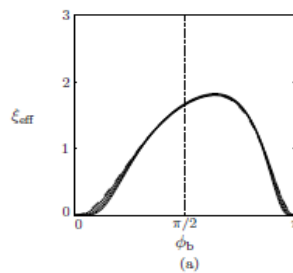
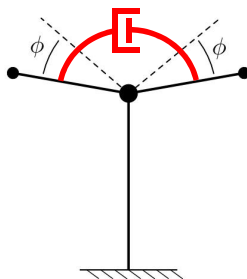
(c)



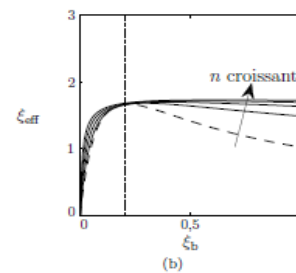
(d)

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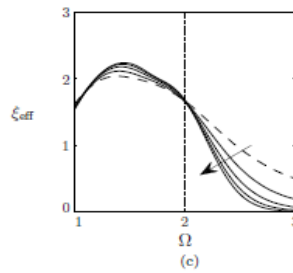
Dépendance paramétrique



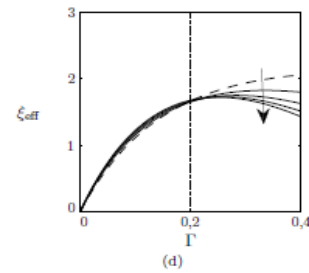
(a)



(b)



(c)



(d)

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

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

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Figure 1 consists of six subplots arranged in a 3x2 grid, labeled (a) through (f). Each subplot shows the effective coupling ξ_{eff} on the y-axis (ranging from 0 to 3) against a different parameter on the x-axis. In all plots, a solid line represents ξ_{eff}^0 and a dashed line represents ξ_{eff}^1 . A vertical dashed line marks the parameter value where the two curves intersect.

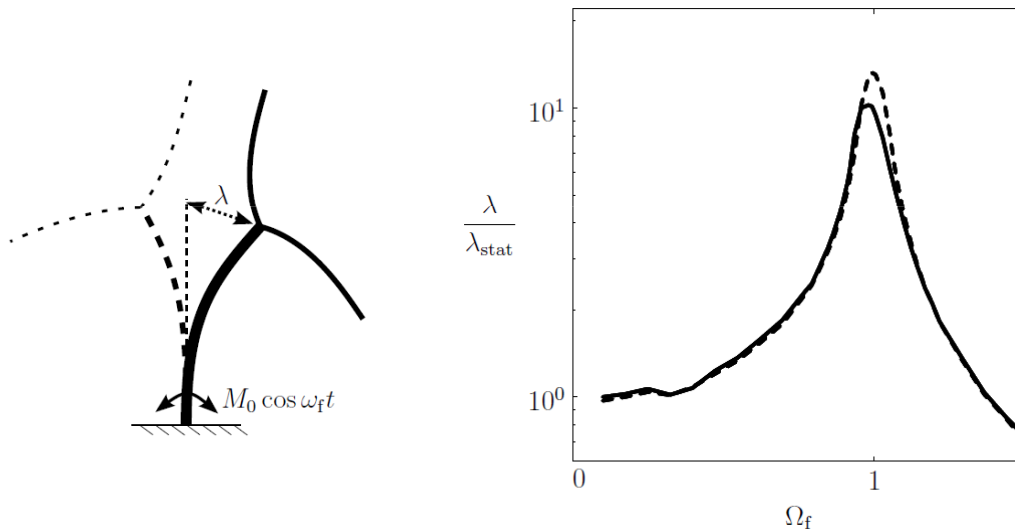
- (a) ξ_{eff} vs ϕ_b : The x-axis ranges from 0 to π . The intersection occurs at $\phi_b = \pi/2$.
- (b) ξ_{eff} vs M : The x-axis ranges from 0 to 1. The intersection occurs at $M \approx 0.25$.
- (c) ξ_{eff} vs Ω : The x-axis ranges from 1 to 3. The intersection occurs at $\Omega = 2$.
- (d) ξ_{eff} vs Γ : The x-axis ranges from 0 to 0.4. The intersection occurs at $\Gamma \approx 0.2$.
- (e) ξ_{eff} vs Λ : The x-axis ranges from 0 to 2. The intersection occurs at $\Lambda = 1$.
- (f) ξ_{eff} vs d : The x-axis ranges from 0 to 4. The intersection occurs at $d \approx 0.5$.

Figure 1 consists of four subplots, (a) through (d), each showing the effective friction coefficient ξ_{eff}/E_0 on the y-axis against a different parameter on the x-axis. Each plot contains three curves: a solid line, a dashed line, and a dotted line.

- (a) ξ_{eff}/E_0 vs ϕ_b . The x-axis ranges from 0 to π , with a vertical dashed line at $\pi/2$. The y-axis ranges from 0 to 6. The solid curve starts at 0, rises to a peak of about 3.5 at $\phi_b \approx \pi/2$, and then drops to 0 at π . The dashed and dotted curves start at 0, rise to a peak of about 5.5 at $\phi_b \approx \pi/2$, and then drop to 0 at π .
- (b) ξ_{eff}/E_0 vs ξ_b . The x-axis ranges from 0 to 1, with a vertical dashed line at $\xi_b \approx 0.2$. The y-axis ranges from 0 to 6. The solid curve starts at 0 and increases monotonically to about 4.5 at $\xi_b = 1$. The dashed curve starts at 0, rises sharply to about 4.5 at $\xi_b \approx 0.2$, and then increases slowly to about 4.8 at $\xi_b = 1$. The dotted curve starts at 0, rises sharply to about 4.5 at $\xi_b \approx 0.2$, and then increases slowly to about 4.5 at $\xi_b = 1$.
- (c) ξ_{eff}/E_0 vs Ω . The x-axis ranges from 1 to 3, with a vertical dashed line at $\Omega = 2$. The y-axis ranges from 0 to 9. The solid curve starts at 0, rises to a peak of about 3.5 at $\Omega \approx 1.5$, and then increases slowly to about 3.8 at $\Omega = 3$. The dashed curve starts at 0, rises to a peak of about 5.5 at $\Omega \approx 1.5$, and then increases slowly to about 6.5 at $\Omega = 3$. The dotted curve starts at 0, rises to a peak of about 4.5 at $\Omega \approx 1.5$, and then increases slowly to about 8.5 at $\Omega = 3$.
- (d) ξ_{eff}/E_0 vs Γ . The x-axis ranges from 0 to 0.4, with a vertical dashed line at $\Gamma \approx 0.2$. The y-axis ranges from 0 to 12. The solid curve starts at 0, rises to a peak of about 3.5 at $\Gamma \approx 0.2$, and then increases slowly to about 3.8 at $\Gamma = 0.4$. The dashed curve starts at 0, rises to a peak of about 4.5 at $\Gamma \approx 0.2$, and then increases slowly to about 4.8 at $\Gamma = 0.4$. The dotted curve starts at 0, rises to a peak of about 4.5 at $\Gamma \approx 0.2$, and then increases slowly to about 4.5 at $\Gamma = 0.4$.

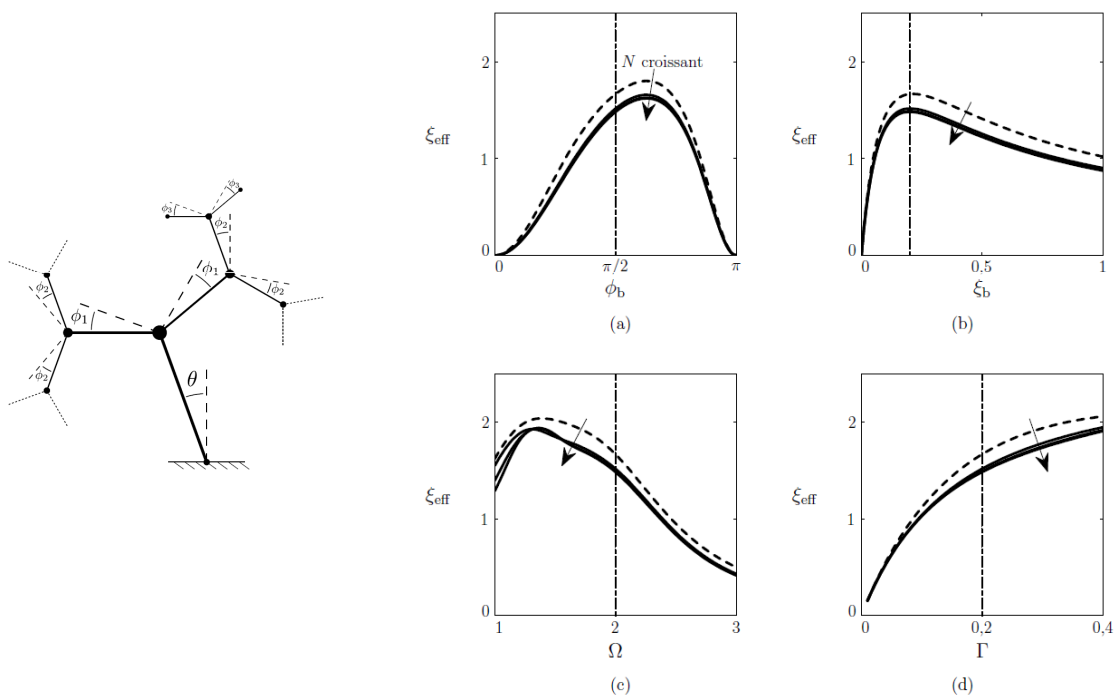
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Forçage du modèle continu



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Dépendance paramétrique



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