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Nonlinear analysis and performance of energy harvesting absorbers with stoppers for controlling fluid-induced vibrations of dynamical systems

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Overview

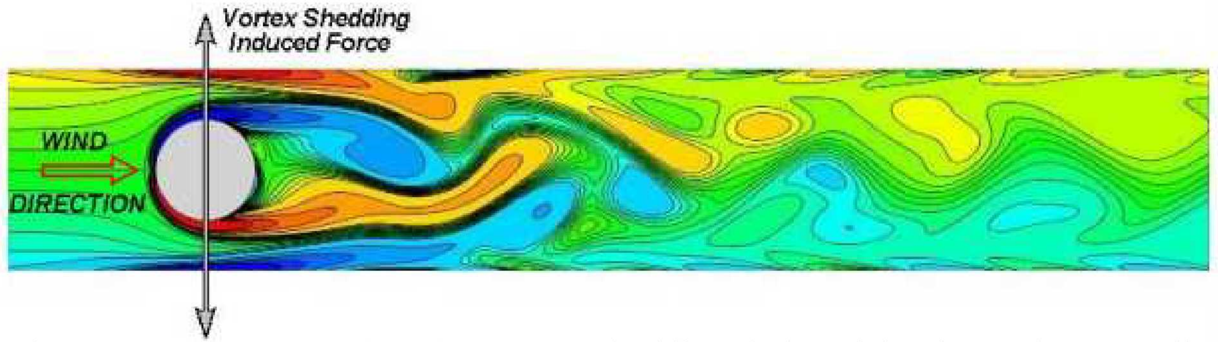
- Background & motivation
- Reduced-order modeling
- Results & discussion
- Future work

Background & motivation

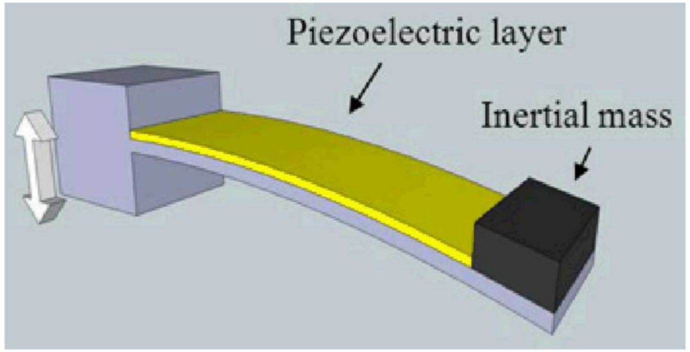
❑ Goals

- Design a vibrational absorber to control the motion of a structure under vortex-induced vibrations
- Utilize an energy harvester as the vibrational absorber to generate useful energy
- Include amplitude stoppers for the energy harvester to generate a broadband region of frequencies.

❑ Vortex-induced Vibration occurs when the vortex sheading frequency of a fluid flowing over a cylindrical bluff body matches the natural frequency of the structure



Giosan, I., & Eng, P. (2013). Vortex shedding induced loads on free standing structures. *Structural Vortex Shedding Response Estimation Methodology and Finite Element Simulation*, *42*.



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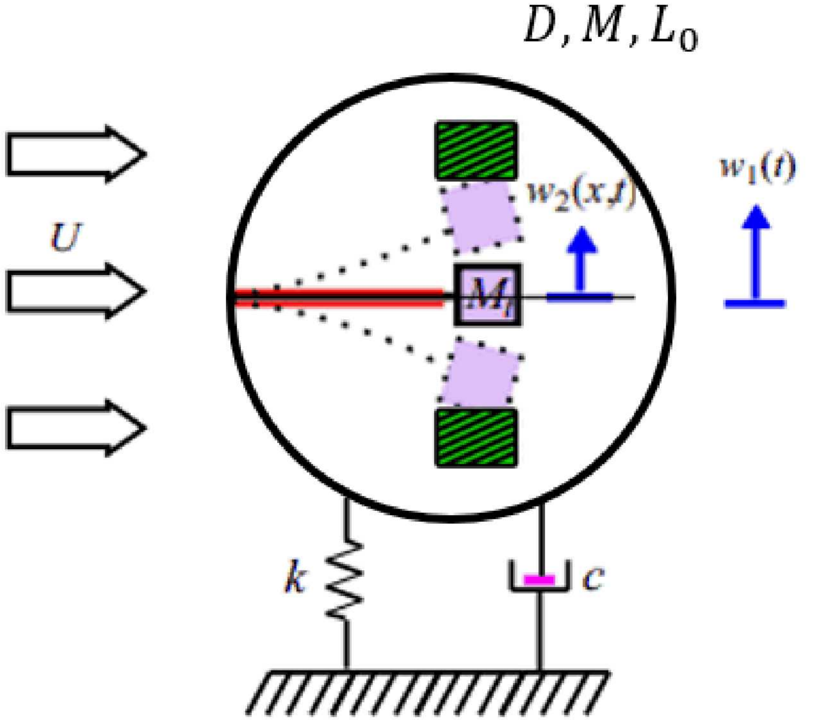
Reduced-order modeling

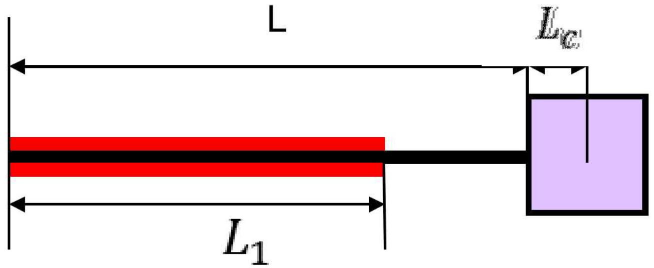
$$T = \frac{1}{2} M \dot{w}_1^2 + \frac{1}{2} M_t \dot{r_2}^2 + \frac{1}{2} I_t w_2(L,t)'^2 + \frac{1}{2} \int_0^L M_b \left(\dot{w}_1 + \dot{w}_2(x,t) \right)^2 dx$$

where

$$\dot{r_2} = \dot{w}_1 + \dot{w}_2(L,t) + L_c \dot{w}_2{}'(L,t)$$

$$I_t = \tfrac{1}{3} M_t L_c^2$$





Reduced-order modeling

$$\Pi = \frac{1}{2}\int_{v_s} \sigma_x^s \varepsilon_x^s dv + \frac{1}{2}\int_{v_s} (\sigma_x^s \varepsilon_x^s - E_3 D_3) dv + \frac{1}{2} k w_1^2$$

where $D_3 = d_3 E_p \varepsilon_x^p - \varepsilon_{33} E_3$

$$\Pi = EI_2 \int_{L_1}^{L} \left(w_2''(x,t)\right)^2 dx + EI_1 \int_0^{L_1} \left(w_2''(x,t)\right)^2 dx + be_{31} \int_0^{L_1} \left(h_s + h_p\right)\left(w_2''(x,t)\right) V(t) dx - \frac{e_{31} b L_1}{h_p} V(t)^2$$

$$+ \frac{1}{2} k w_1^2$$

where $EI_1 = \frac{1}{2} b E_s \frac{h_s^3}{12} + \frac{1}{2} h_s^2 h_p + h_s h_p^2 + \frac{2}{3} h_p^3$

$$EI_2 = \frac{1}{2} b E_s \frac{h_s^3}{12}$$

Reduced-order modeling

Galerkin discretization: $w_2 = \sum_{i=1}^{\infty} \varphi_i(x) r_i(t)$

- Energy harvesting absorber mode shapes $\varphi_i(x)$
- General coordinate $r_i(t)$

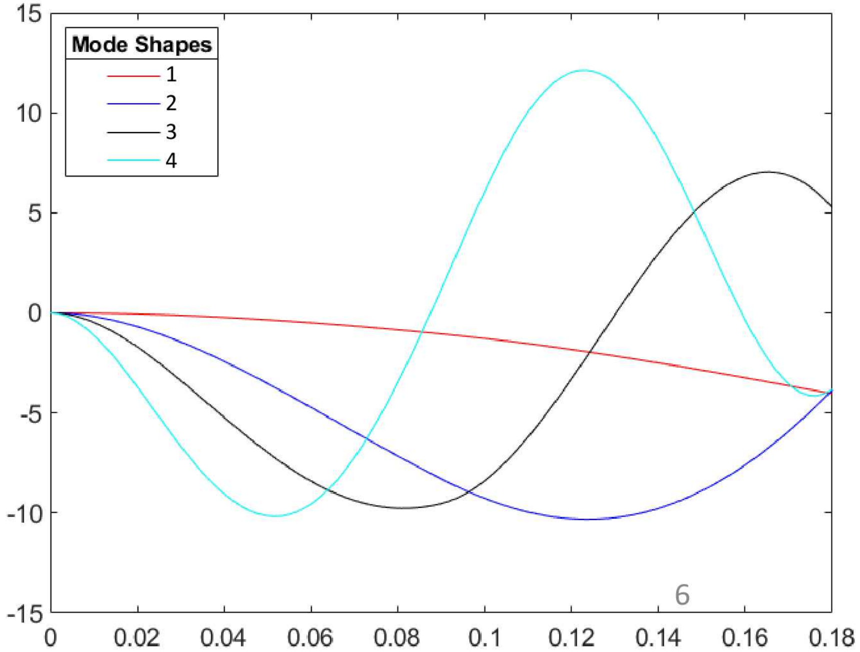
$$(M + M_t + M_b L)\ddot{w}_1 + c\dot{w}_1 + k w_1 + \sum_{i=1}^{\infty} \left(M_t \varphi_i(L) + M_t L_c \varphi_i'(L) + M_b \int_0^L \varphi_i(x) dx \right) \ddot{r}_i = \frac{C_{L0}\rho_0 D U_0^2 L_0}{4} q - \frac{C_D \rho_0 D U_0 L_0}{2} \dot{w}_1$$

$$\ddot{r}_i + 2\xi_i \omega_i \dot{r}_i + \omega_i r_i + \left(M_t \varphi_i(L) + M_t L_c \varphi_i'(L) + M_b \int_0^L \varphi_i(x) dx \right) \ddot{w}_1 - \theta_i V = F_{stopper}$$

$$C_p \dot{V} + \frac{1}{R} + \sum_{i=1}^{\infty} \theta_i \dot{r}_i = 0$$

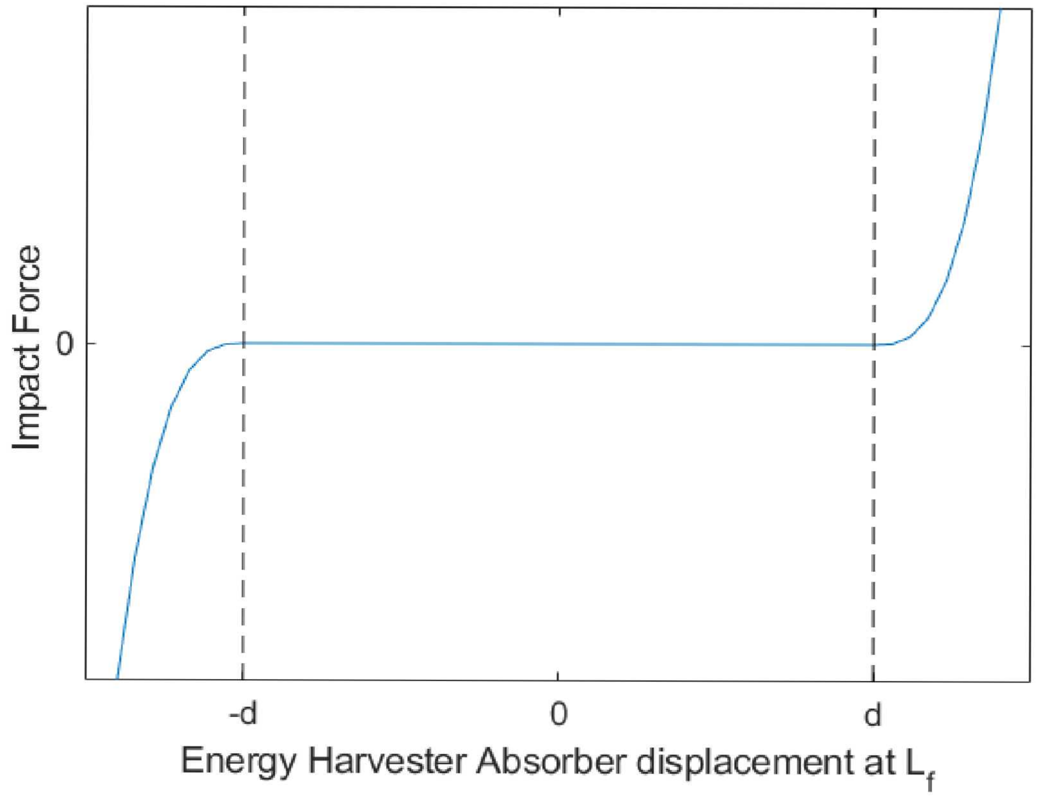
$$\ddot{q} + \Lambda \omega_s (q^2 - 1)\dot{q} + \omega_s^2 q = \frac{A}{D} \ddot{w}$$

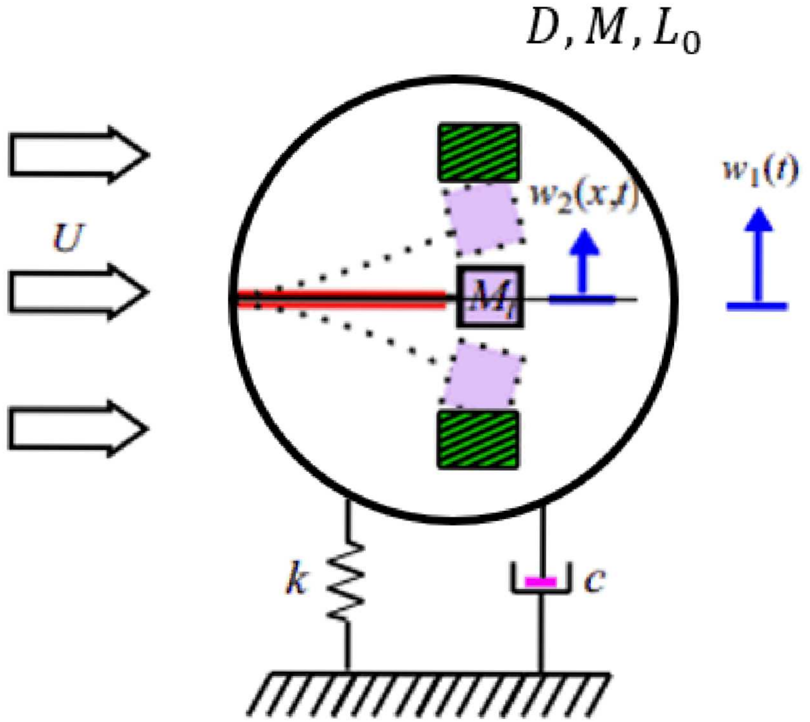
where $C_p = 2\frac{e_{33} b L}{h_p}$, $\theta = E_p d_{31} b (h_p + h_s) \varphi_i'(L)$



Reduced-order modeling

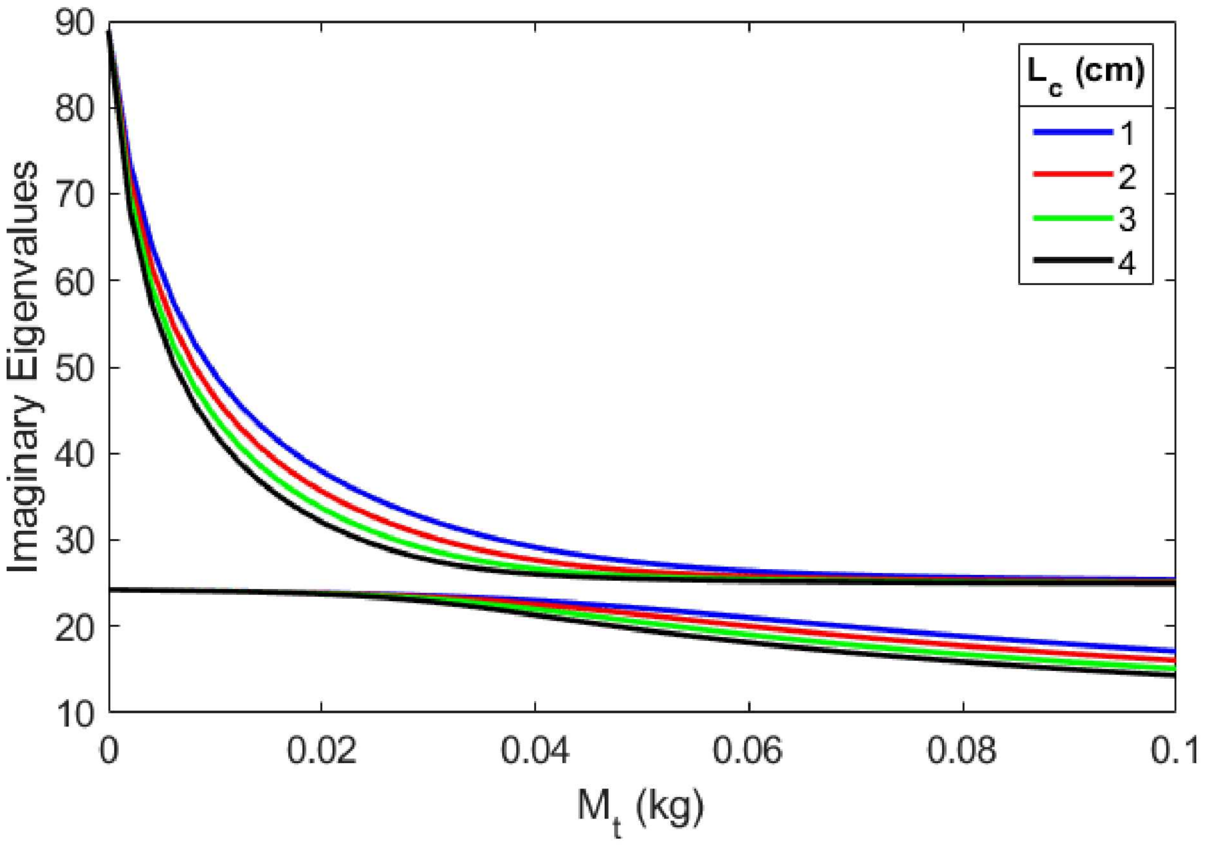
$$F_{stopper} = k\left[\sum_{i=1}^{\infty}\varphi_i(x)r_i(t) - \frac{1}{2}\left(\left|\sum_{i=1}^{\infty}\varphi_i(x)r_i(t)+d\right|\right) - \left(\left|\sum_{i=1}^{\infty}\varphi_i(x)r_i(t)-d\right|\right)\right]^3$$

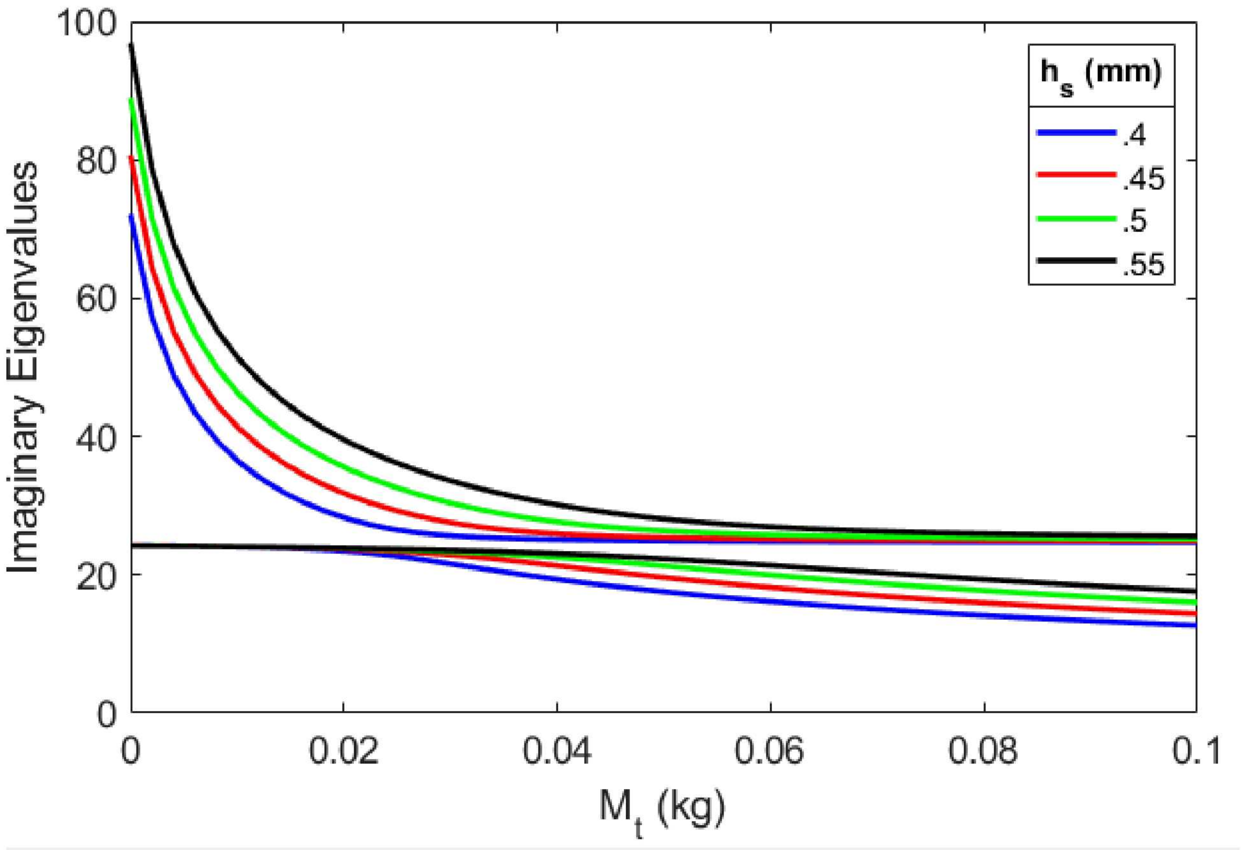




Linear analysis

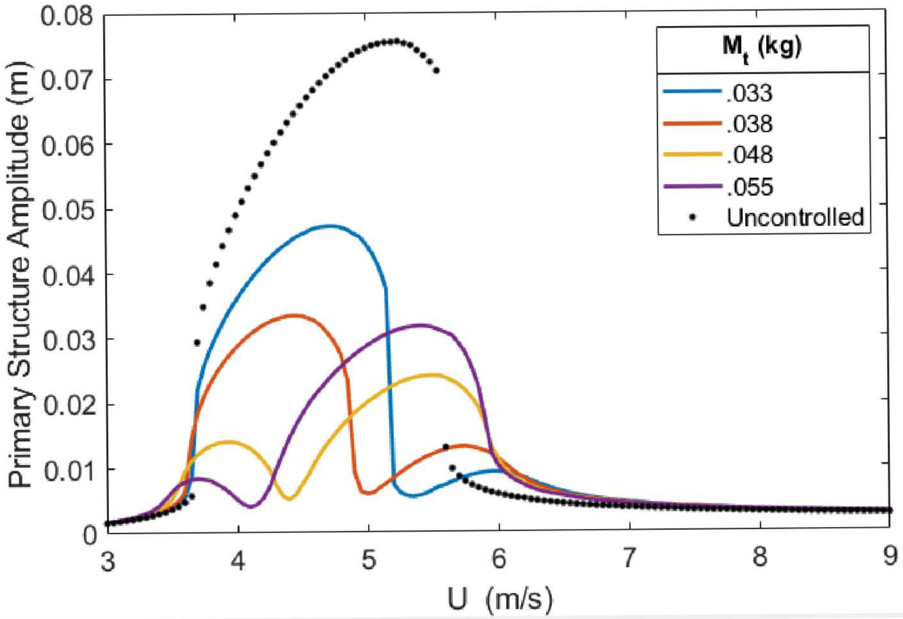
Imaginary eigenvalues analyzed to find parameters' values where the coupled natural frequencies are close to each other to force control of the primary structure

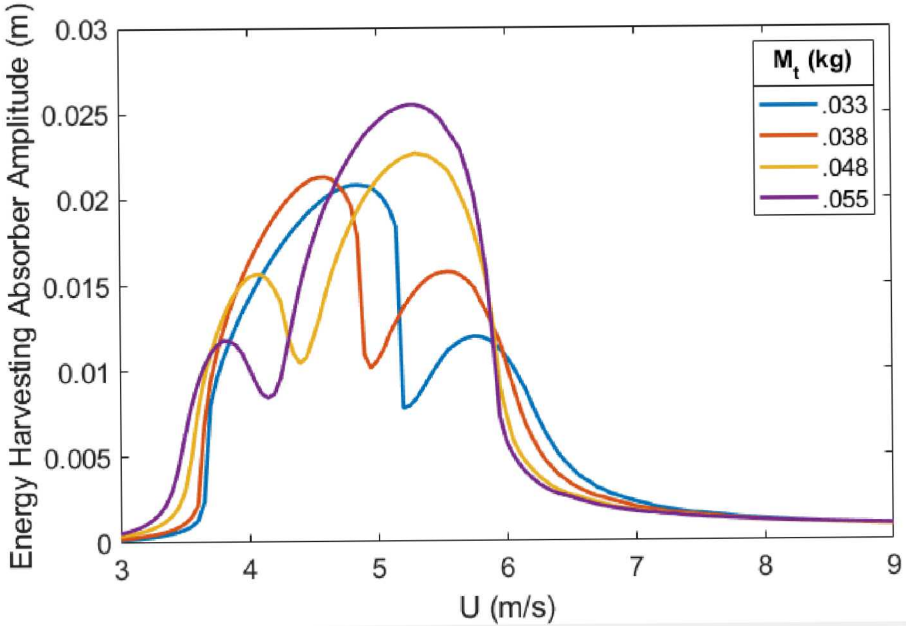


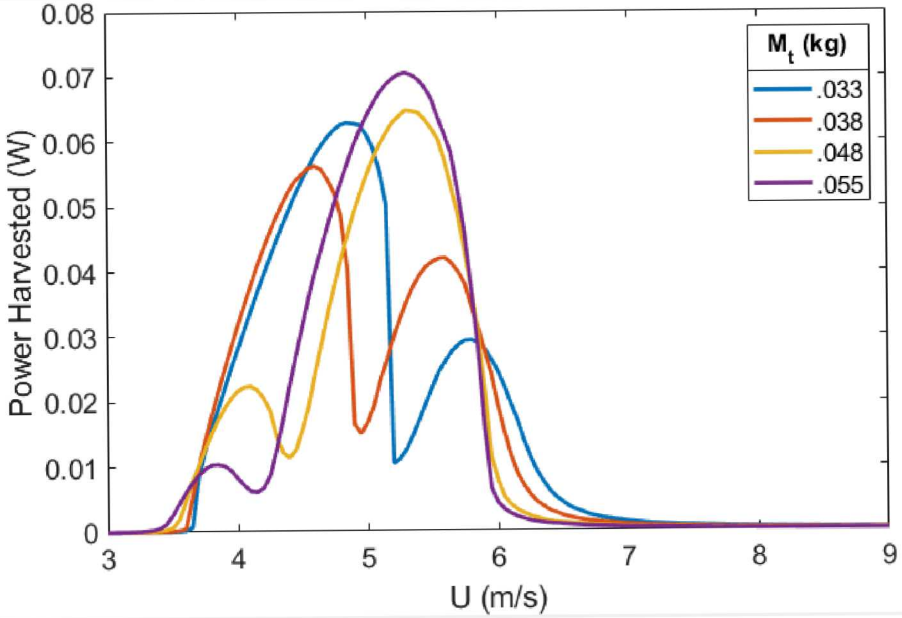


Results – Control of the structure

Parameter Values	
L_c	2 cm
h_s	.5 mm
h_p	.267 mm
R	$10^{4.73}\ \Omega$
L	1.8 cm

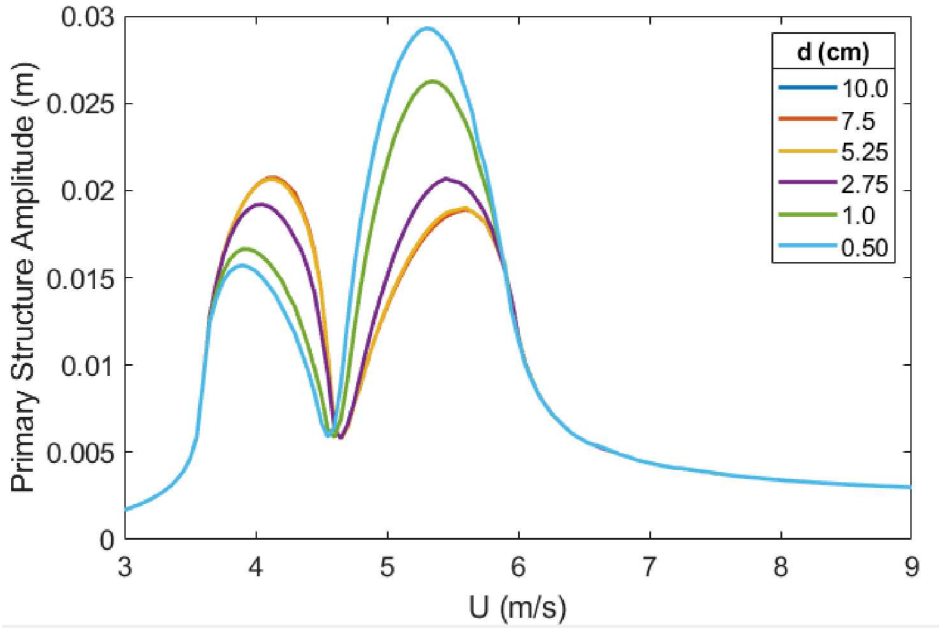


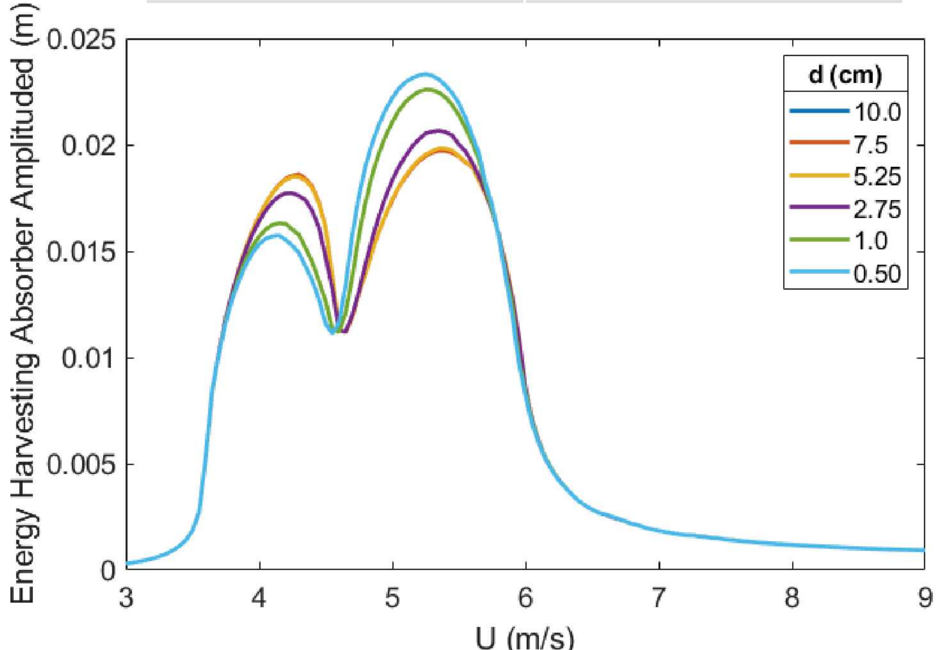


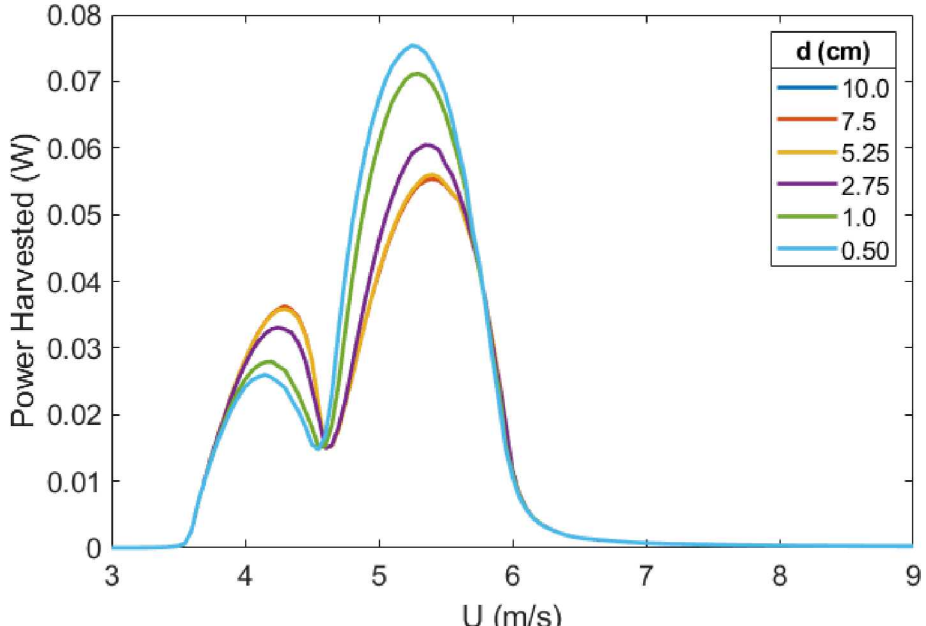


Results – Stoppers' gap effects

Parameter Values	
L_c	2 cm
h_s	.5 mm
h_p	.267 mm
R	$10^{4.73}\ \Omega$
L	1.8 cm
L_s	1.8 cm
M_t	.0435 kg

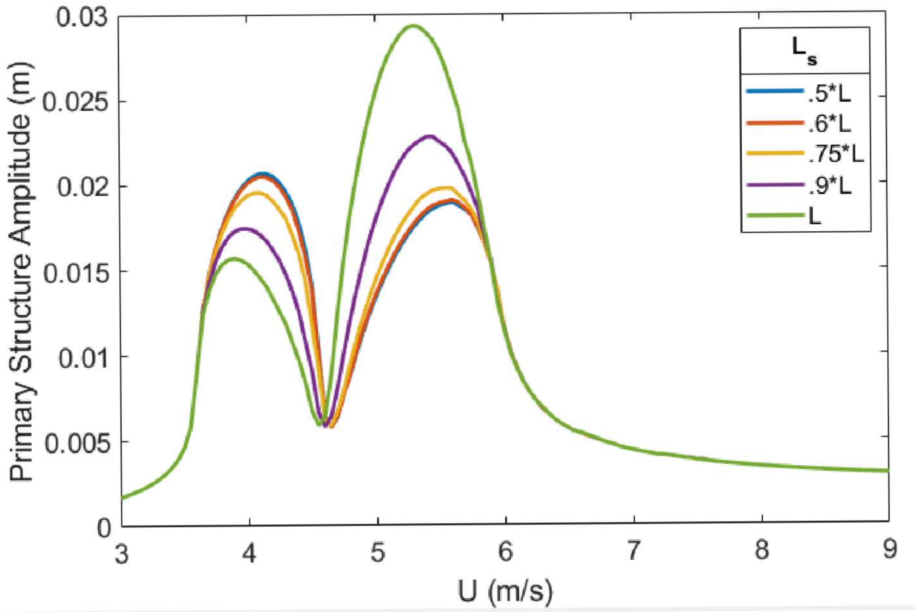


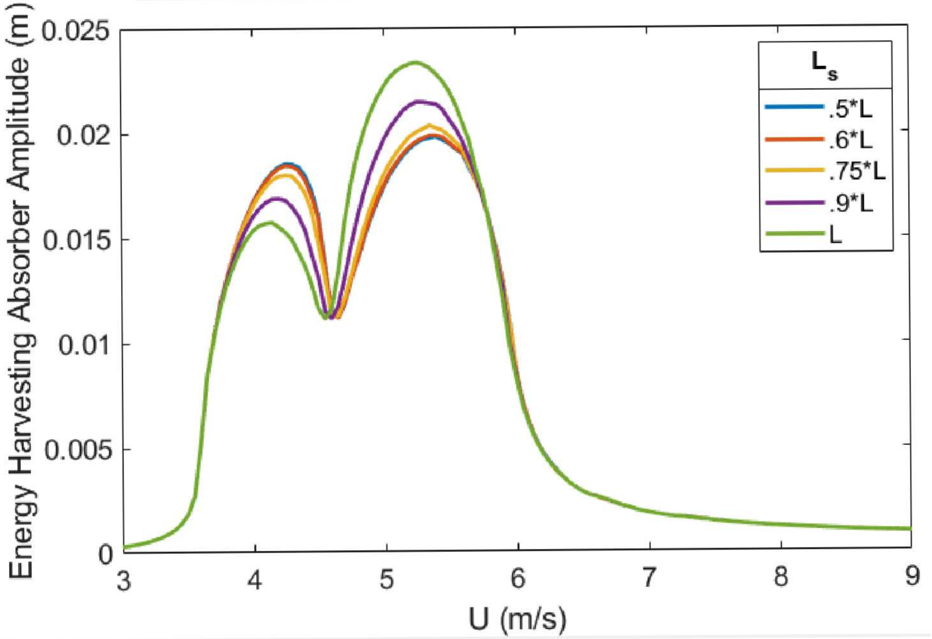


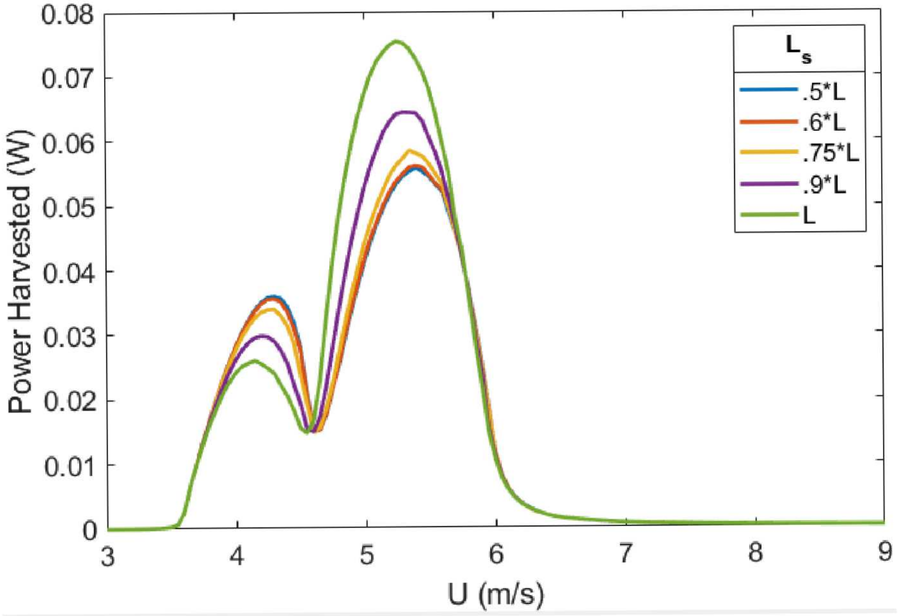


Results – Stoppers' location effects

Parameter Values	
L_c	2 cm
h_s	.5 mm
h_p	.267 mm
R	$10^{4.73}\ \Omega$
L	1.8 cm
d	.5 cm
M_t	.0435 kg

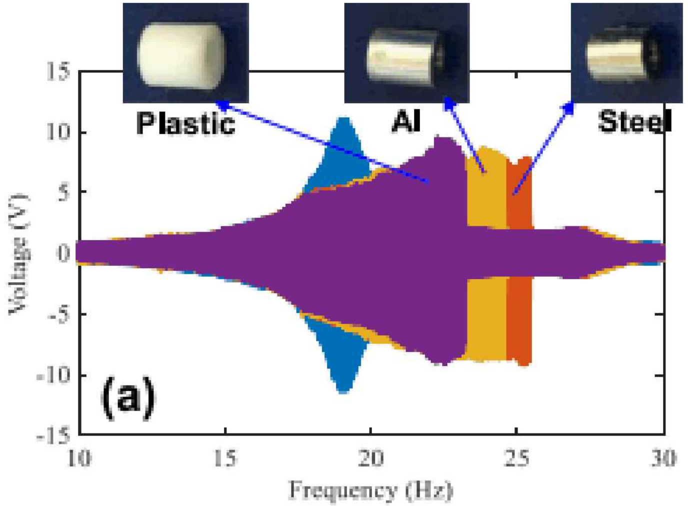






Future Work

- Investigation of different stopper stiffnesses/materials
- Modal convergence study
- Different types of stoppers (mechanical, magnetic, etc.)



Zhou, K., Dai, H. L., Abdelkefi, A., Zhou, H. Y., & Ni, Q. (2019). Impacts of stopper type and material on the broadband characteristics and performance of energy harvesters. *AIP Advances*, *9*(3), 035228.

Acknowledgements

Thank you for your attention.

Questions?