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Global stabilization of high-energy resonance for a nonlinear wideband electromagnetic vibration energy harvester

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Outline

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- Introduction
  - Idea of nonlinear wide-band vibration energy harvesters
  - Well-known difficulty - coexistence attractors
- Proposition: use of the principle of self-excitation and entrainment
  - Load resistance switching
  - Global stability of highest-energy solution
- Experimental verification
  - Steady-state
  - Transient
- Conclusions

Wide-band vibration energy harvester (VEH)

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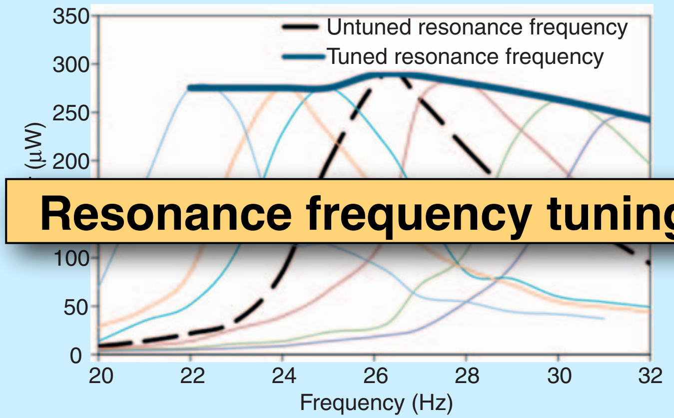
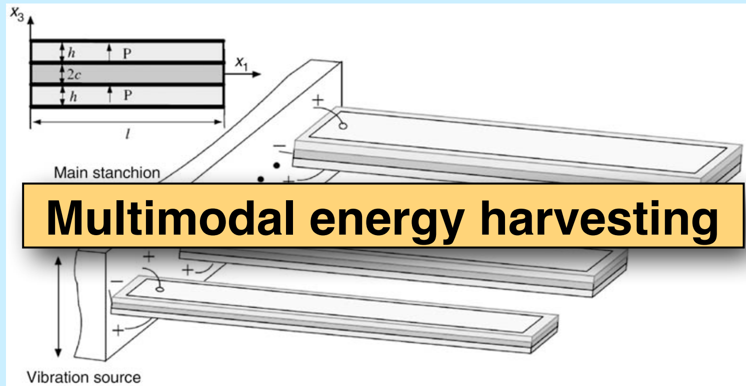
- Linear energy harvester has “power-bandwidth trade-off”.
- Four categories of wider-band energy harvester: (Tang et al., 2010)

Resonance frequency tuning



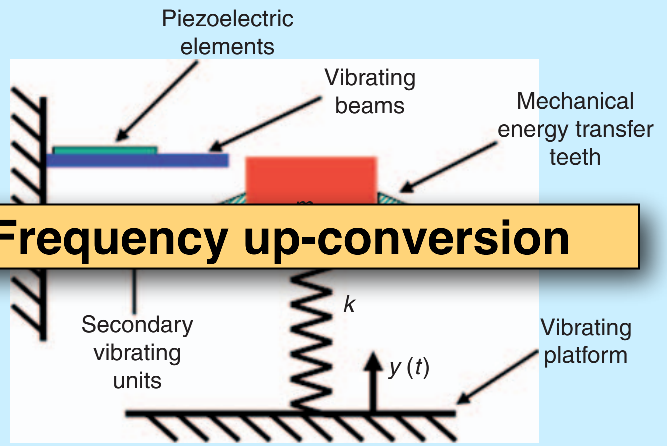
Challa et al., Smart Mater. Struct., 2008

Multimodal energy harvesting



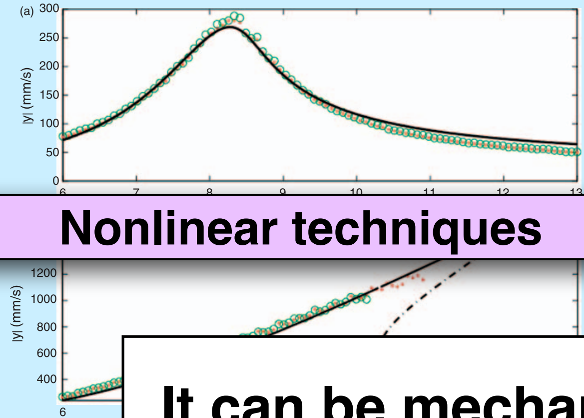
Xue et al., IEEE Trans. Ultrason. Ferroelectr. Freq. Control, 2008

Frequency up-conversion



Rastegar et al., Proc. SPIE, 2006

Nonlinear techniques



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It can be mechanically simpler than others.

Duffing-type nonlinear VEH

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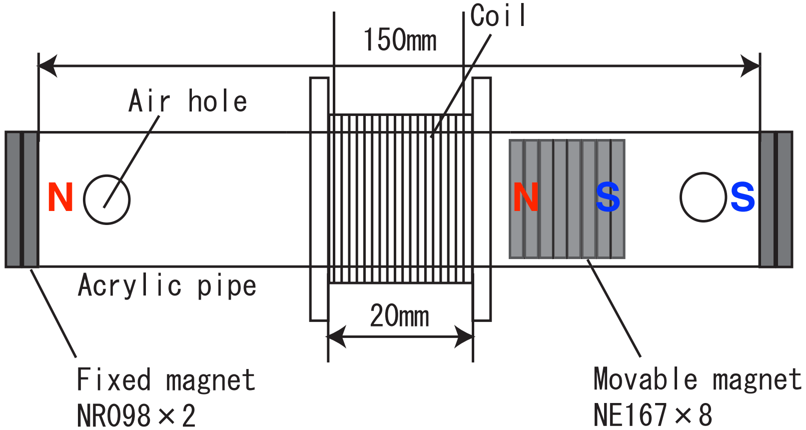
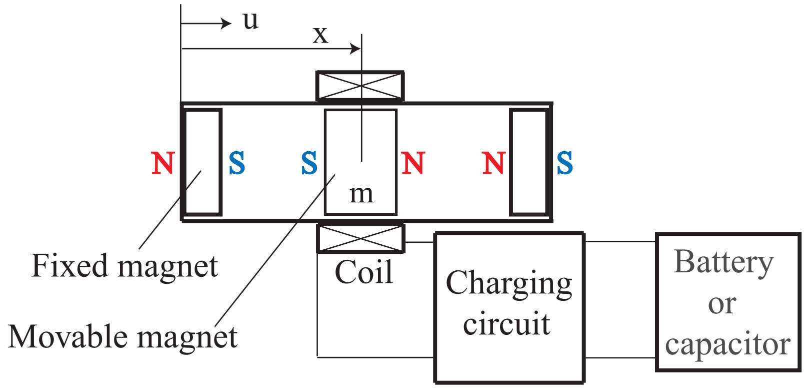
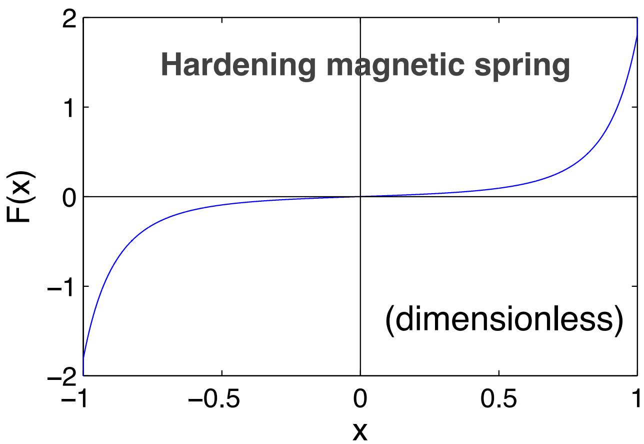
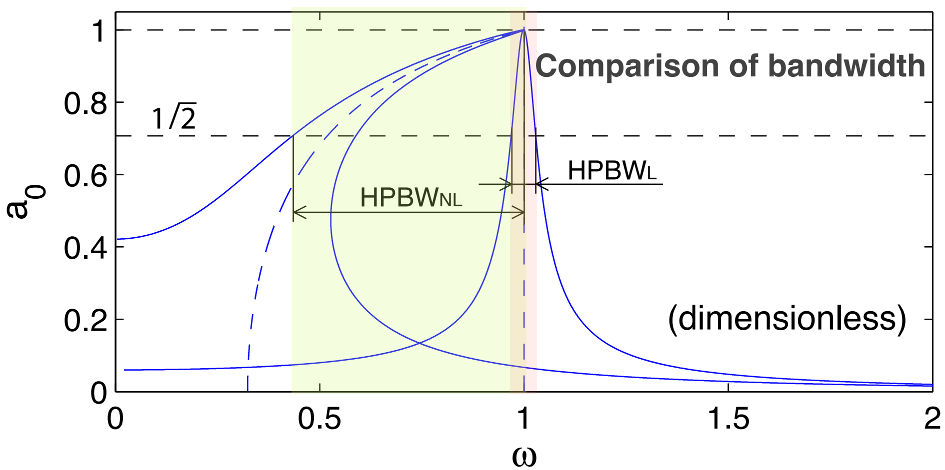
- One of the most promising approaches.
- Moving/ fixed magnets, repulsive force, induction coils.
- This config can provide a significant wider bandwidth than linear.









Two stable branches of Duffing-type oscillator

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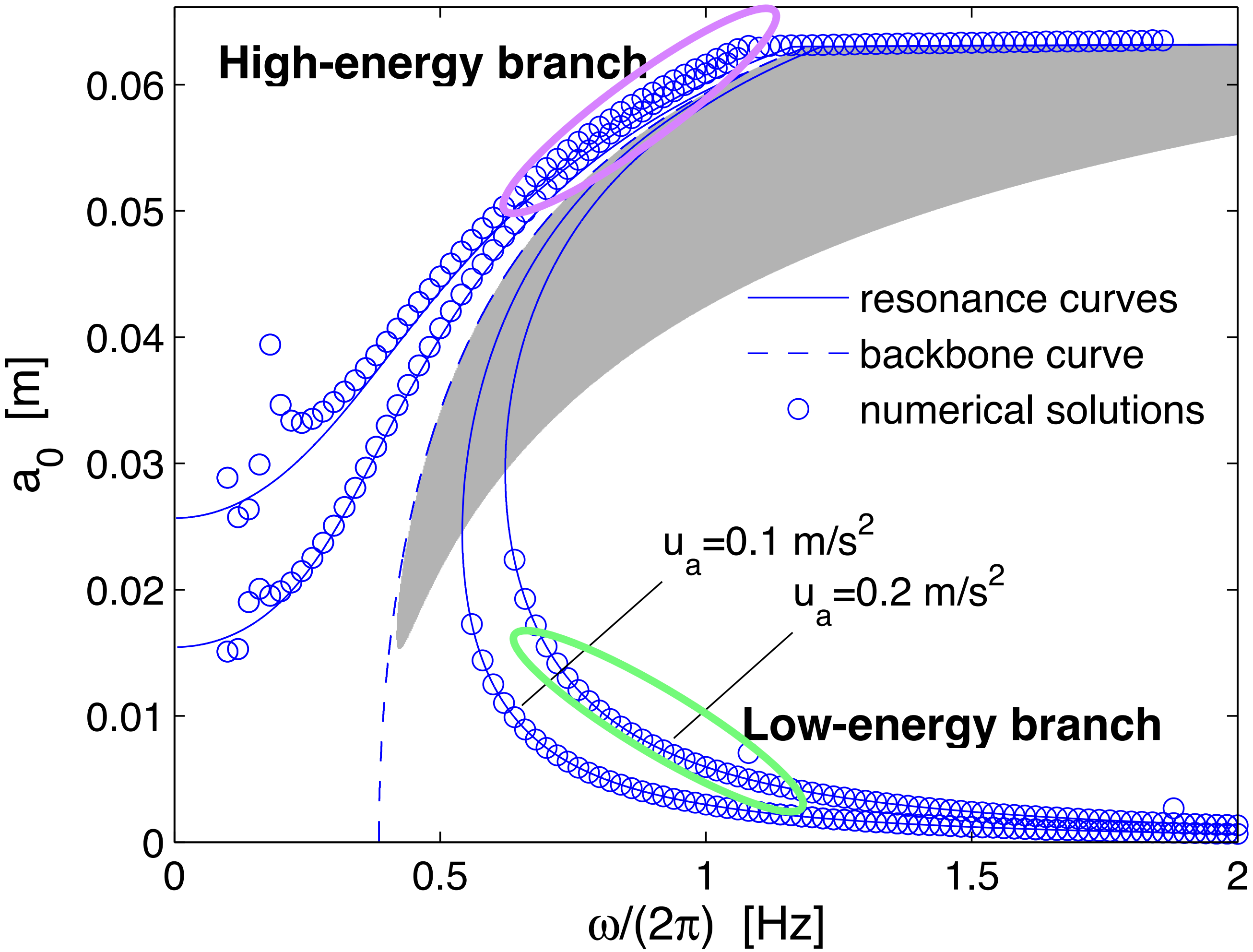

Grayed region indicates where the steady-state response is unstable

Basins of attraction

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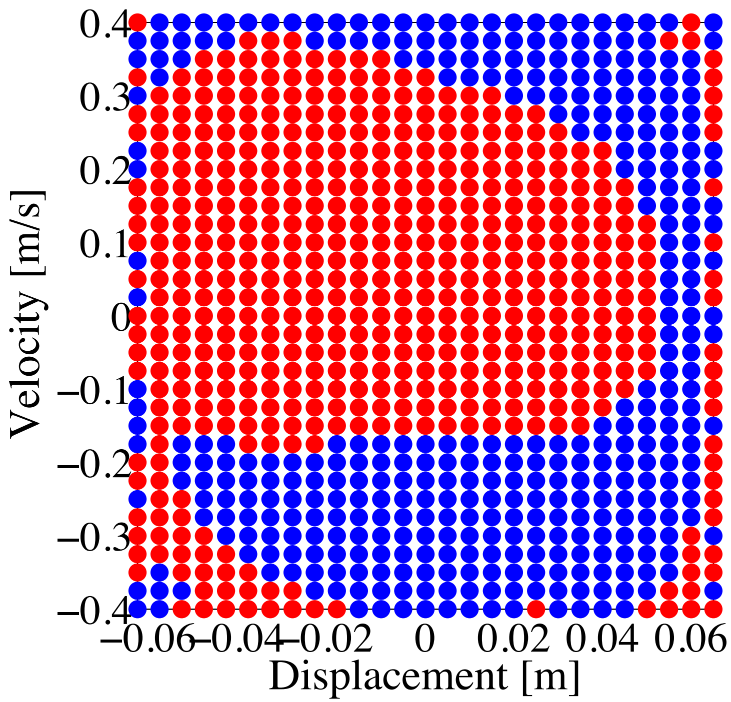
- The set of initial conditions that lead to high-energy solution: blue
- The set of initial conditions that lead to low-energy solution: red



Basins of attraction of two solutions (attractors) at a certain Poincaré map.

Even if the system is responding in the high-energy solution, it can easily drop down to the low-energy solution when subjected to disturbances.

Abrupt change of excitation frequency

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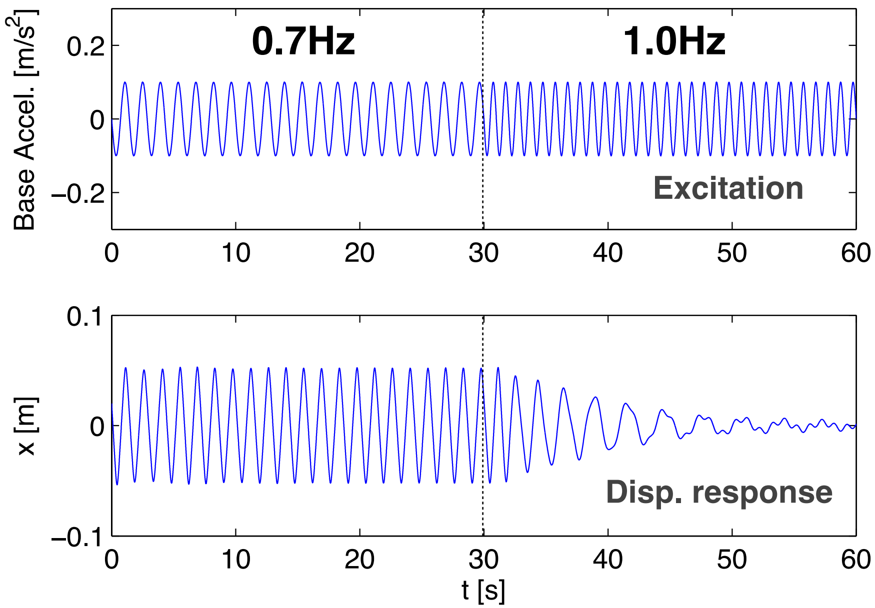
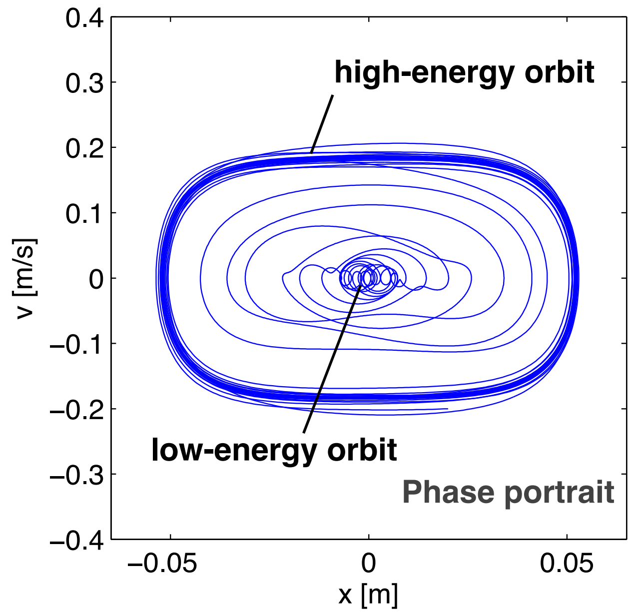
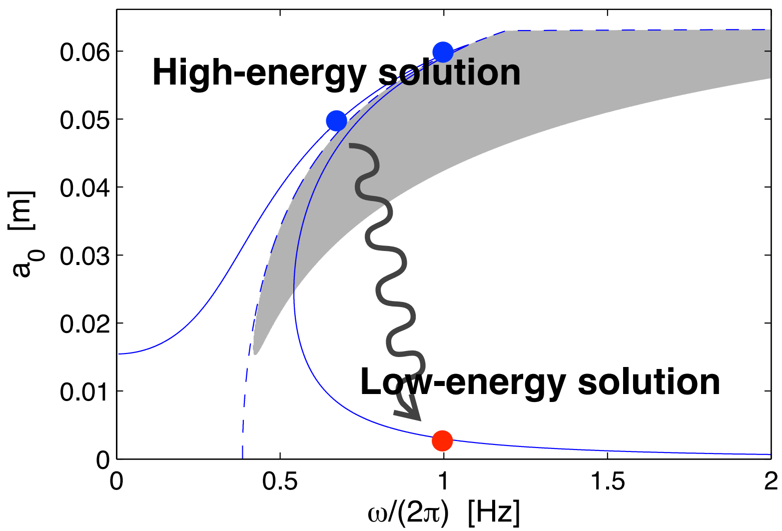
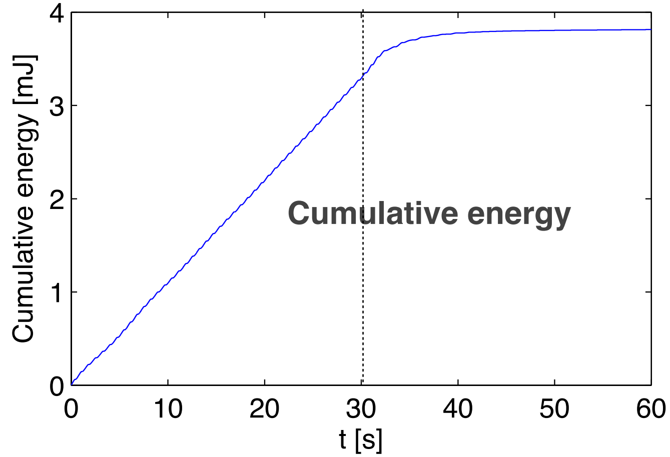


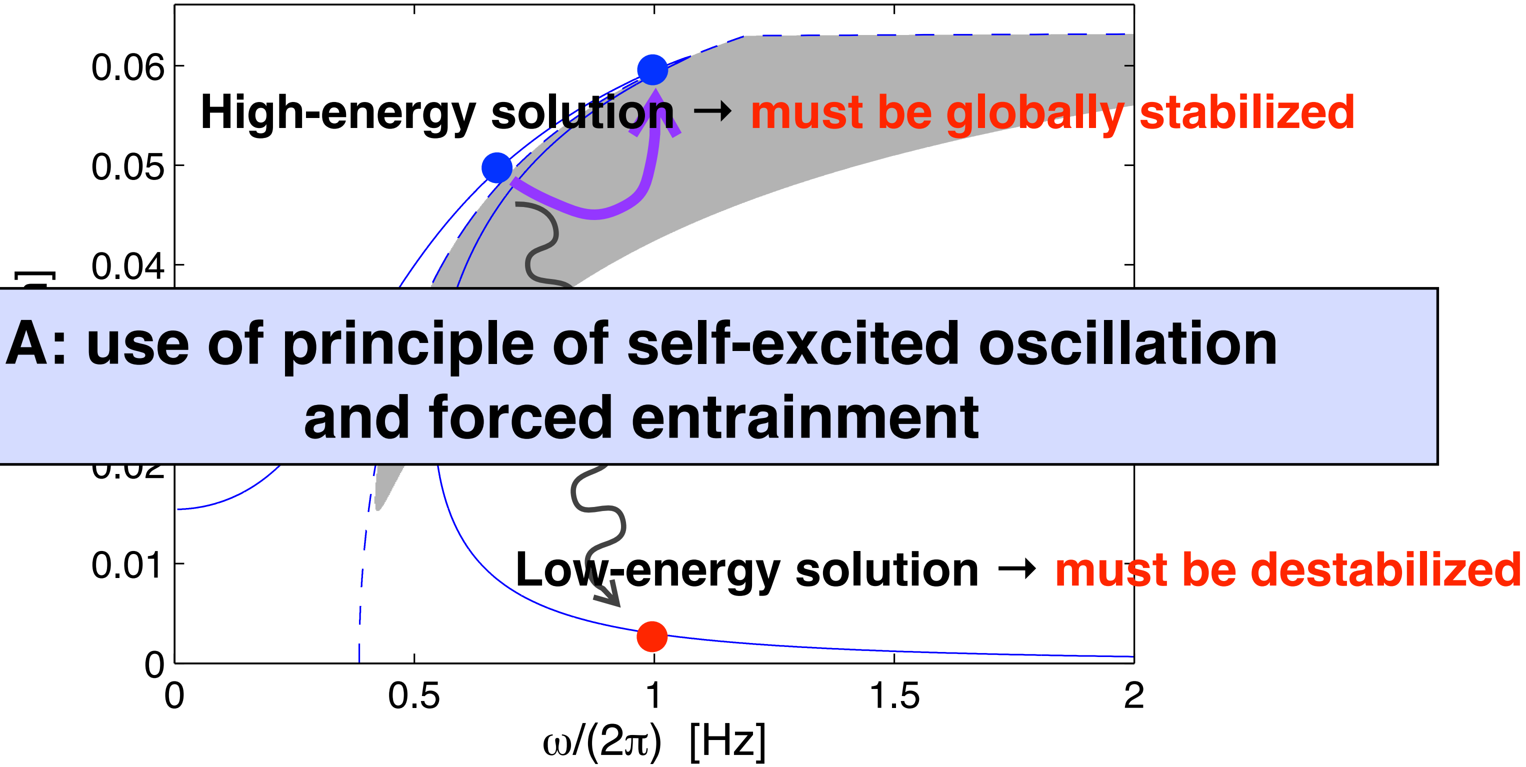






How can we keep the response large?

- We have to think of some mechanism to maintain the response on the high-energy solution even if the disturbance pushes the response out of the solution. → Global stabilization
- Done by destabilizing the low-energy solution.
- Q: how it is realized?



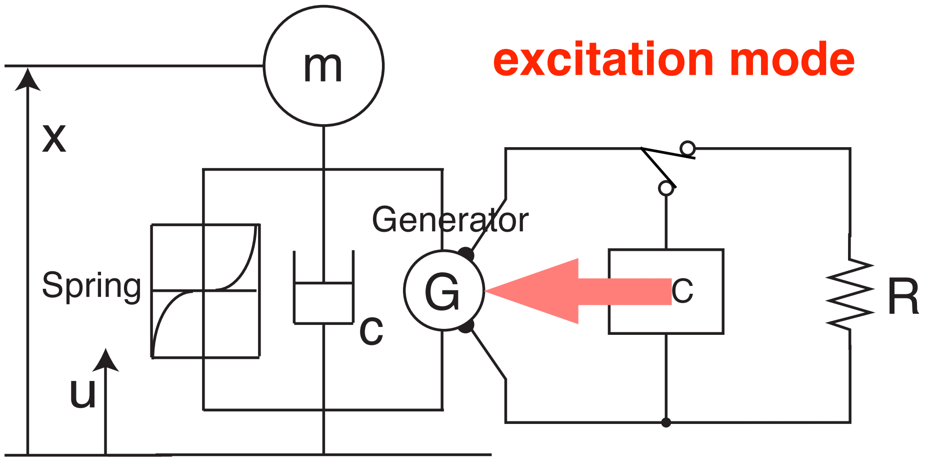
A: use of principle of self-excited oscillation and forced entrainment

Load resistance switching

- Harvesting mode: normal harvesting circuit
- Excitation mode: self-excitation circuit with negative resistance
- Proposition: switch the circuit between harvesting/ excitation modes according to the displacement amplitude.

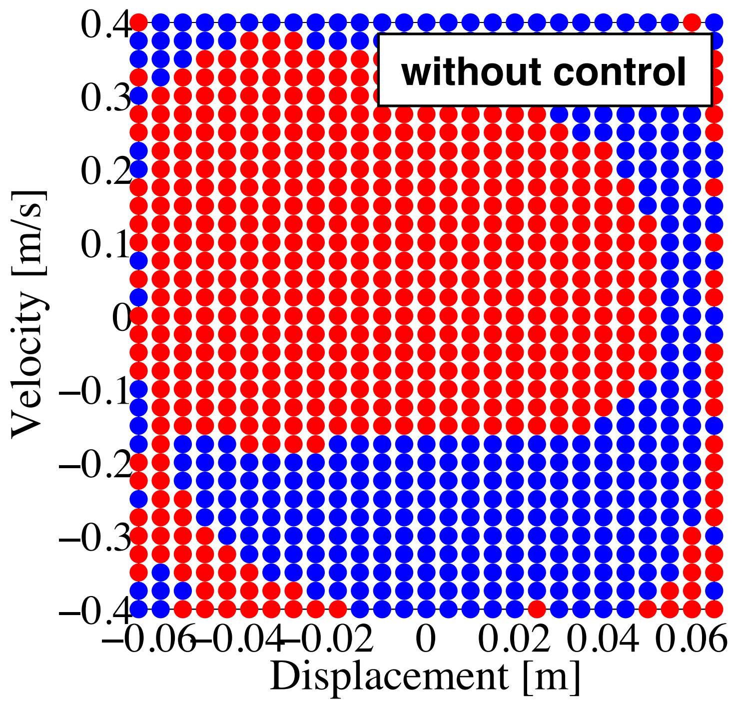
$$R(a) = \begin{cases} R_{positive} & (a \geq a_\theta); \quad \text{harvesting mode} \\ R_{negative} & (a < a_\theta); \quad \text{excitation mode} \end{cases}$$

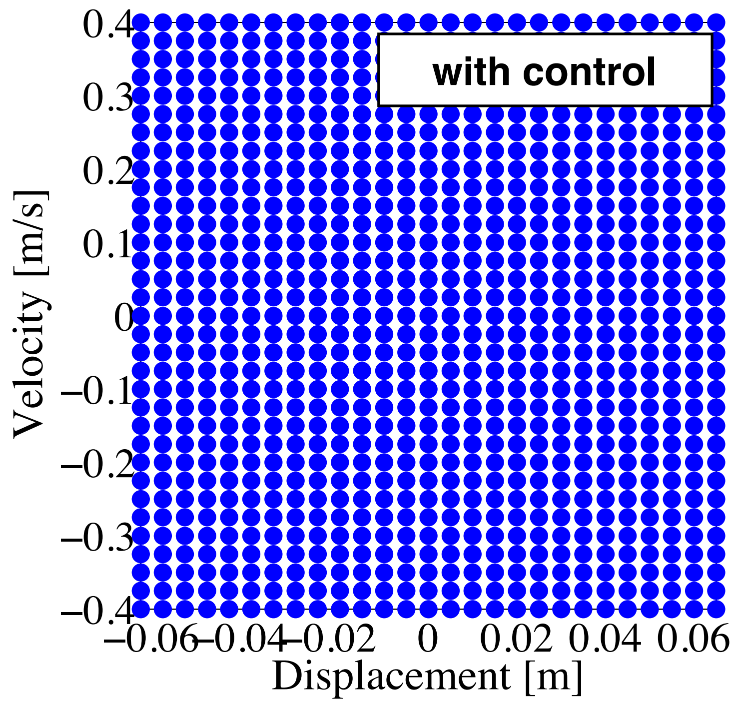
- This simple control law makes the system perform as self-excitation vibratory system, which is expected to yield "forced entrainment".



Basins of attraction

- The set of initial conditions that lead to high-energy solution: blue
- The set of initial conditions that lead to low-energy solution: red





Basins of attraction are drastically changed by introducing the proposed control law.

Basin of low-energy solution disappears. The high-energy solution has been globally stabilized.

Abrupt change of excitation frequency

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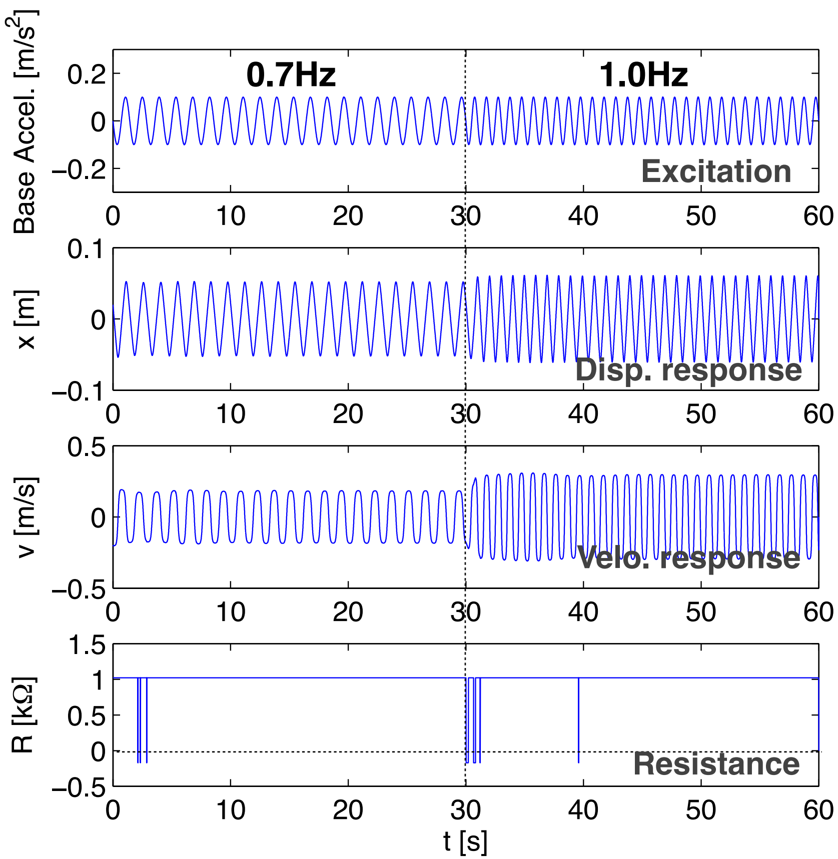
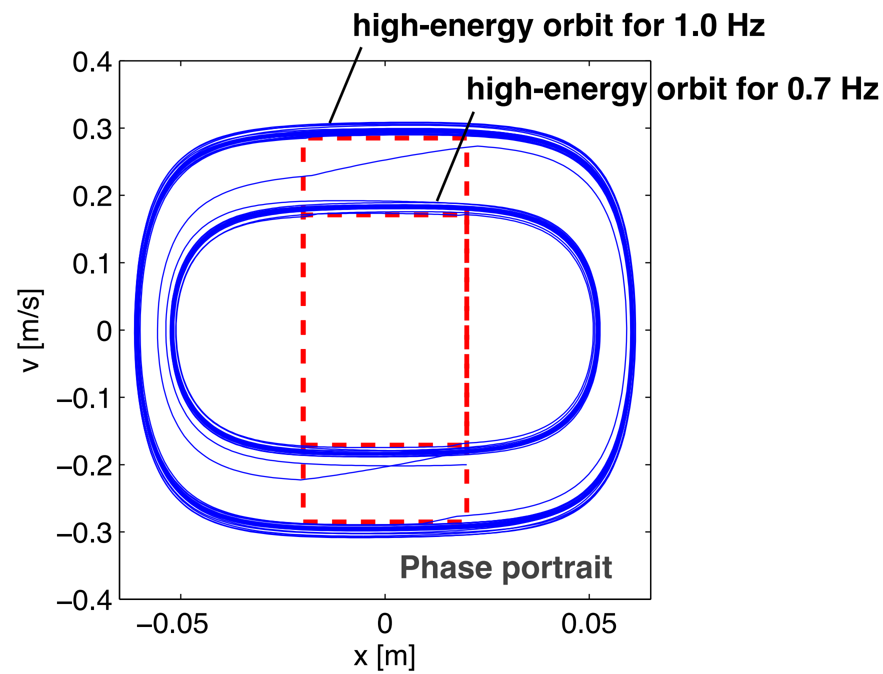
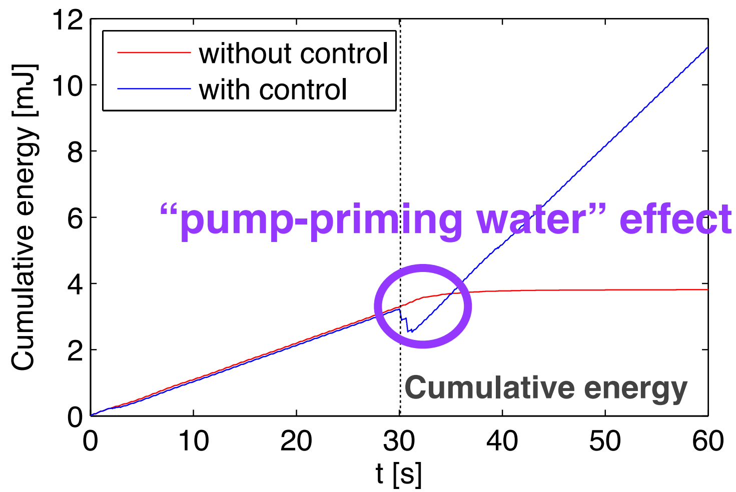


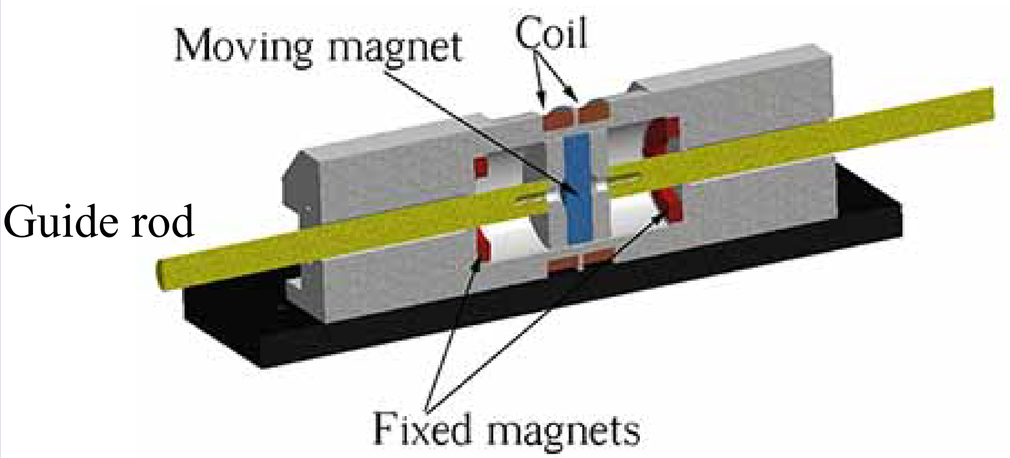


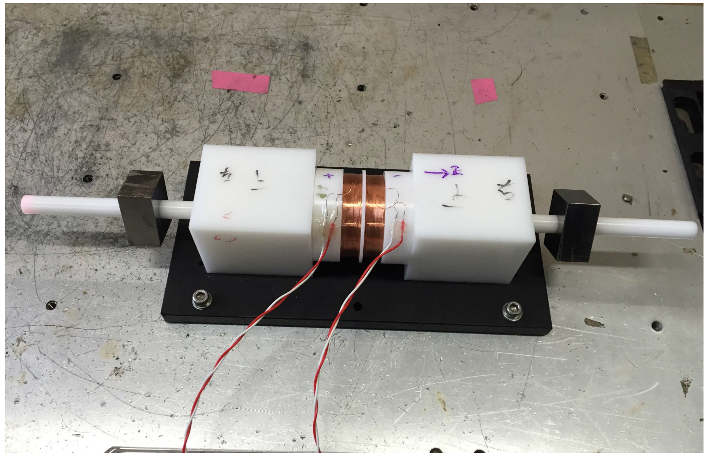


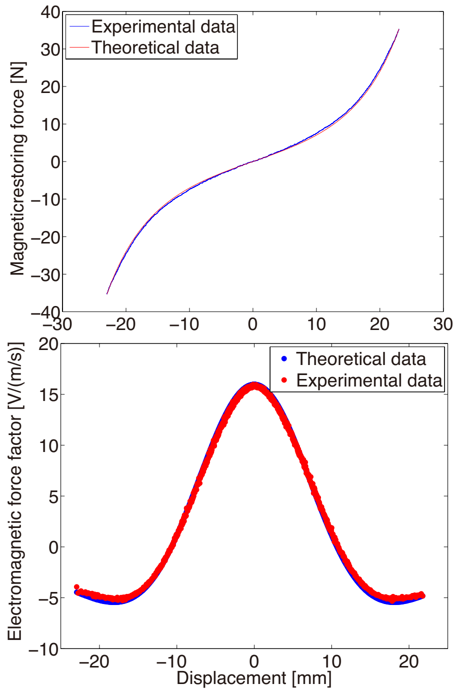
Experimental verification

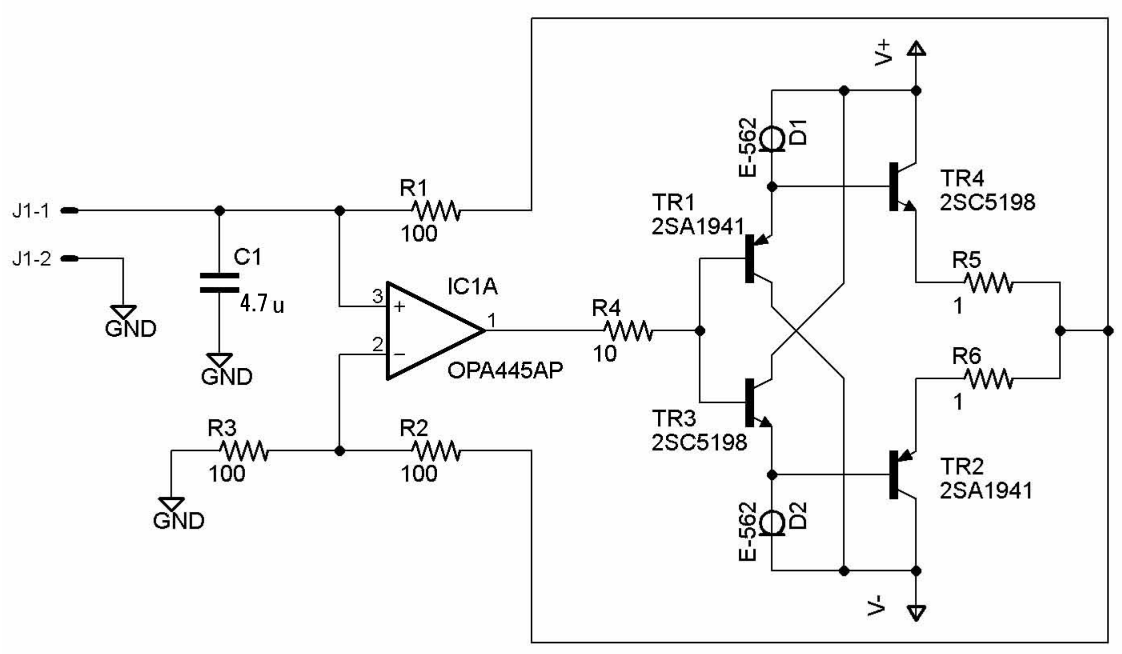
- Large-scale (L=23 mm, 100mW, 7.2 Hz) conceptual prototype
- Steady-state experiments
  - Forward/backward-swept sinusoidal excitation
  - Resonance curves
- Transient experiments
  - Impulsive disturbance

Conceptual prototype (L=23 mm, 100 mW, 7.2 Hz)









Experimental setup

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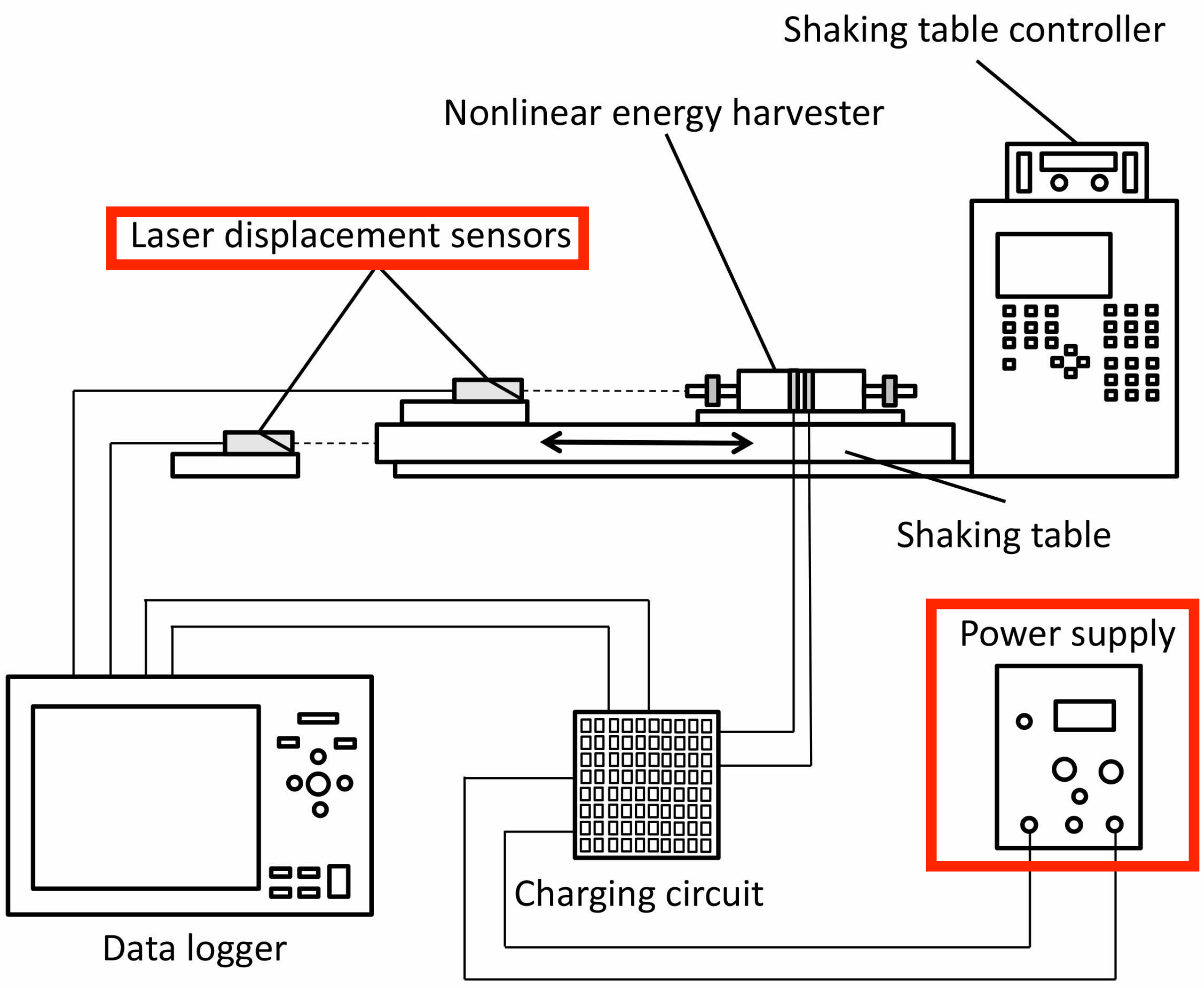
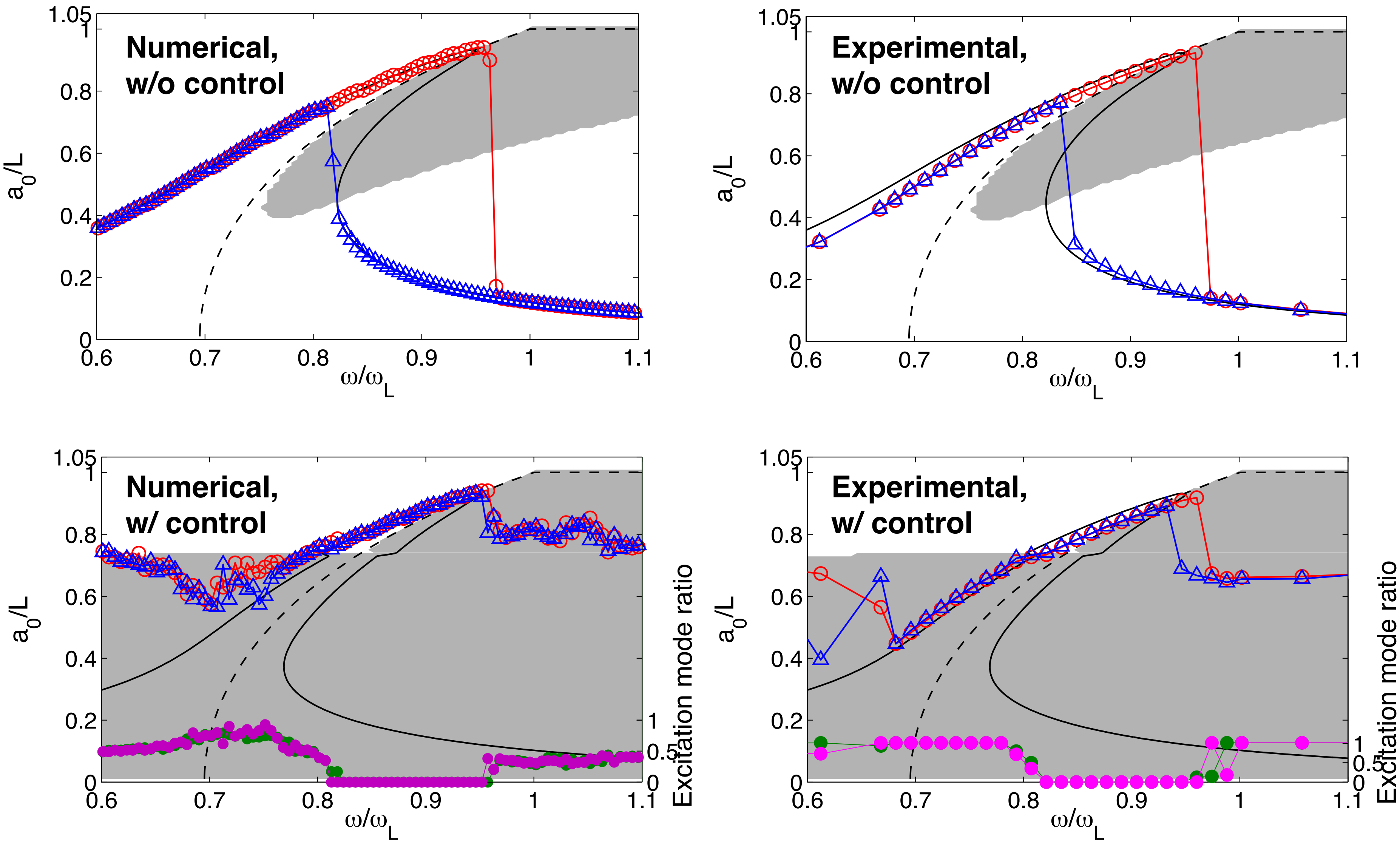


Experiment #1: steady-state

- Excite the harvester with sinusoidal swept waves in upward/downward directions (u_a=0.3 g).
- Experimental results are compared with
  - theoretical solutions derived from a mathematical model by averaging method;
  - numerical solutions derived from the mathematical model by MATLAB ode45 function.

Results #1: Steady-state responses



Experiment #2: transient

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- First excite the harvester in high-energy solution by sinusoidal wave in 6.6 Hz (u_a=0.3 g).
- Hit the end of the guide rod by hammer to see the transient response to the impulsive disturbance.

Transient response to impulsive disturbance

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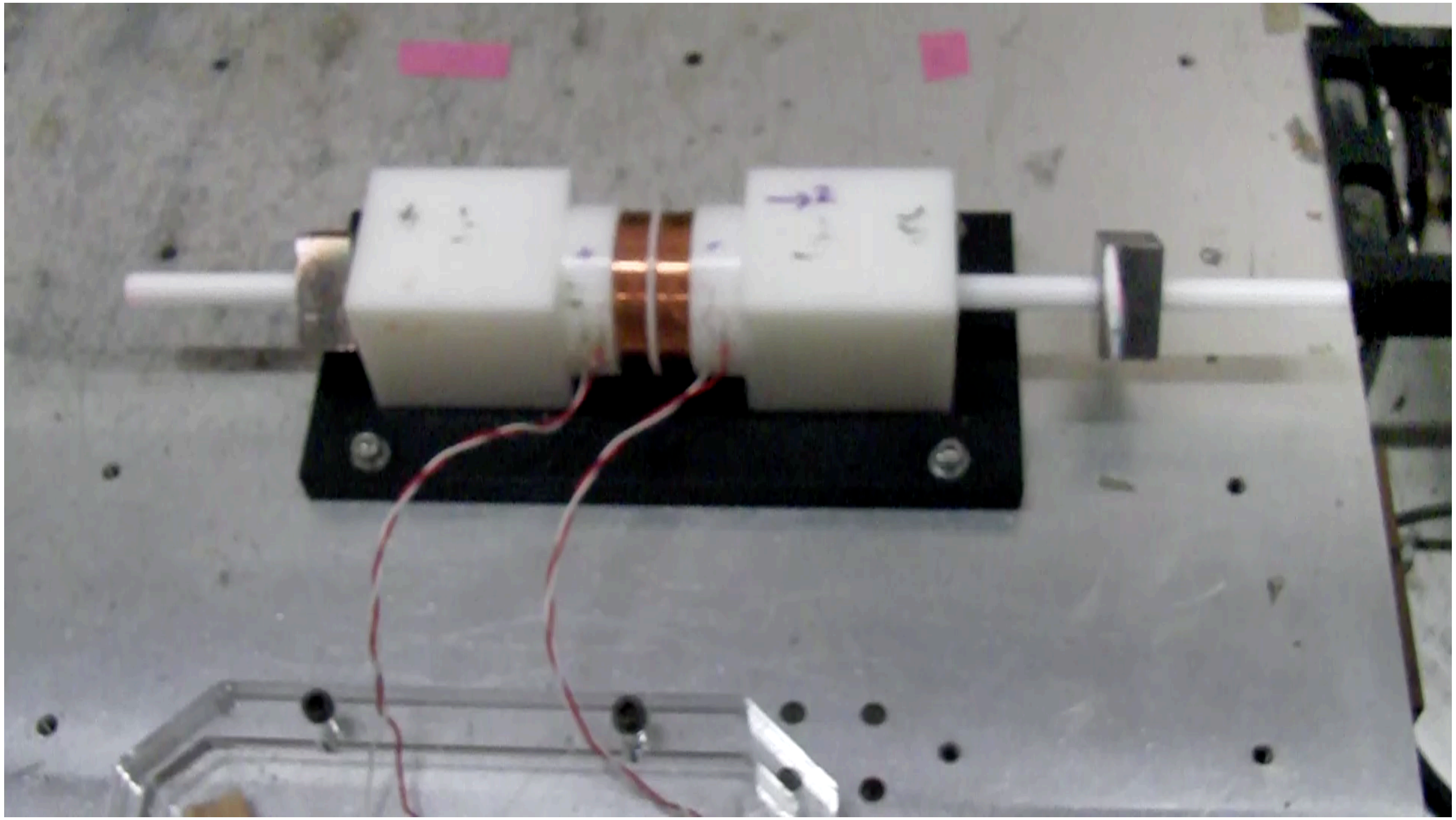

Response w/o control

Transient response to impulsive disturbance

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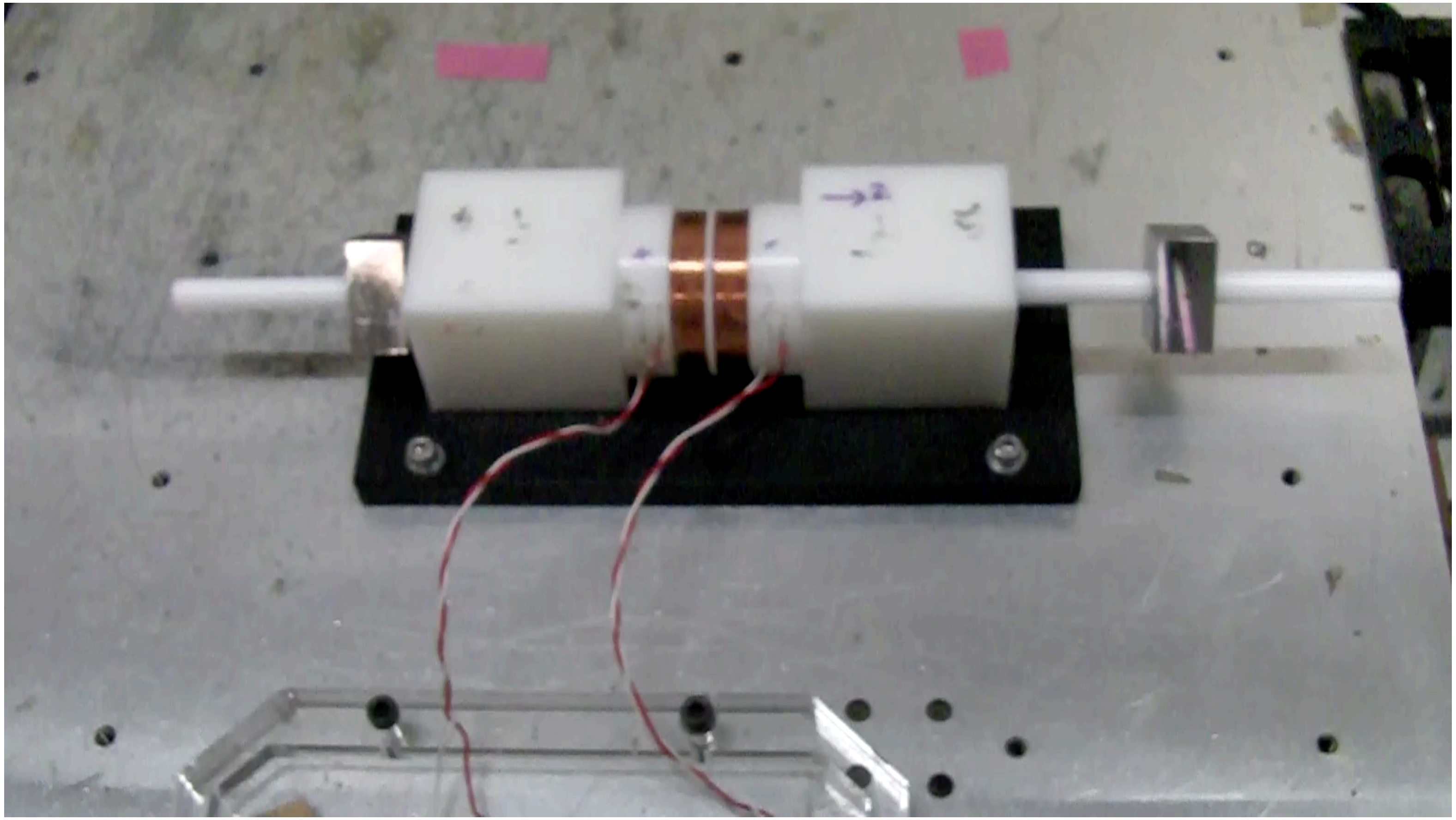

Response w/ control

Transient responses

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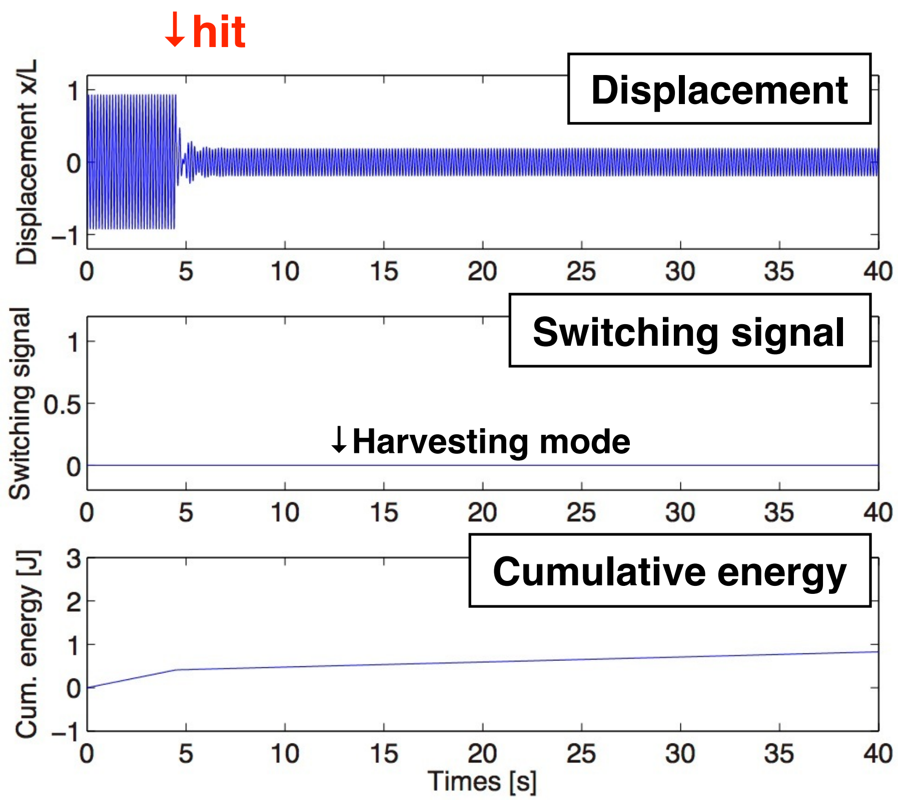

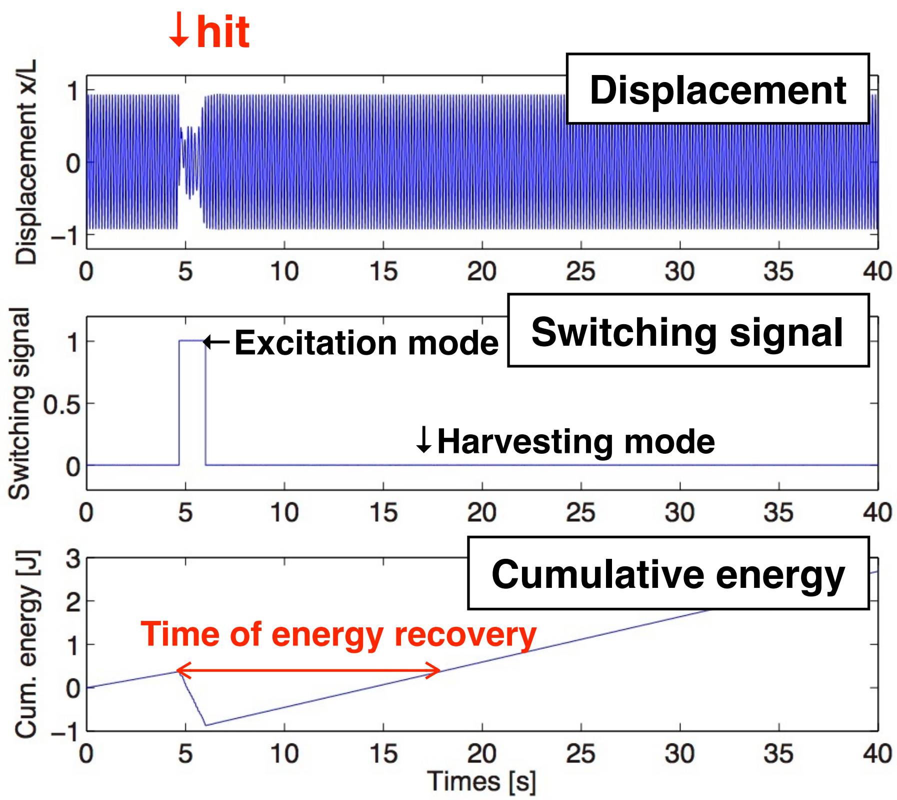

Response w/o control **Response w/ control**

Conclusions

- In order to overcome the difficulty of coexistence solutions in a Duffing-type nonlinear energy harvester, a self-excitation technique is proposed.
- By switching the circuits between the harvesting and excitation modes, the proposed harvester can respond in the high-energy solution even subjected to the disturbance.
- The experimentally obtained steady-state response of the harvester well agreed with the solutions derived from the mathematical model.
- It was concluded from both the steady-state and transient experiments that the proposed load resistance switching successfully destabilized the low-energy solution and made the high-energy solution globally stable.