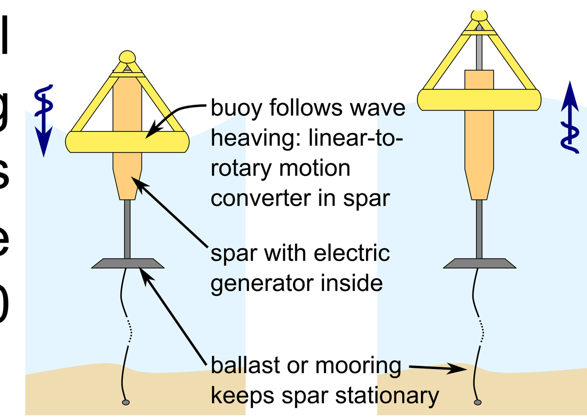
Multi-stable chain for vibration energy harvesting using interconnected bistable links

Michel E. Schoemaker, Dr. R.L. Harne, and Prof. K.W. Wang

UNIVERSITY OF MICHIGAN

Motivation

The power of heaving waves is a largely untapped energy resource. Capturing the kinetic energy for portable, mobile marine applications could integrate with solar technology for round-the-clock, sustainable power supplies. Yet commercialized, high-capacity wave energy conversion technology is inefficient on small scales. Current vibration energy harvesting concepts are suitable for small-scale systems but are inefficient in wave environments where typical excitation periods are close to 10 seconds and displacements are large.

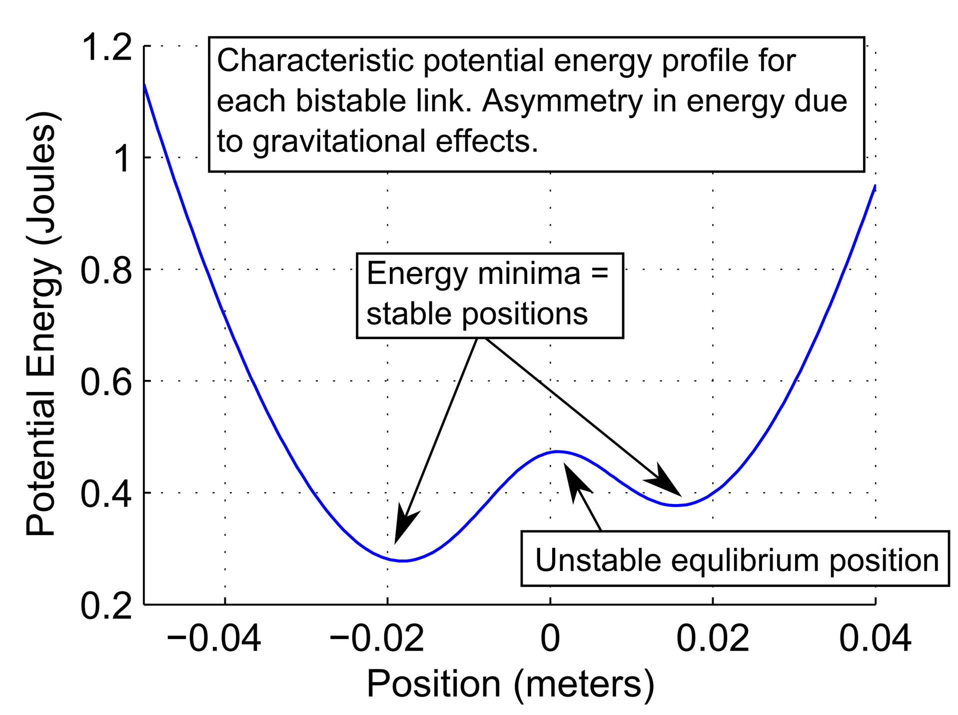


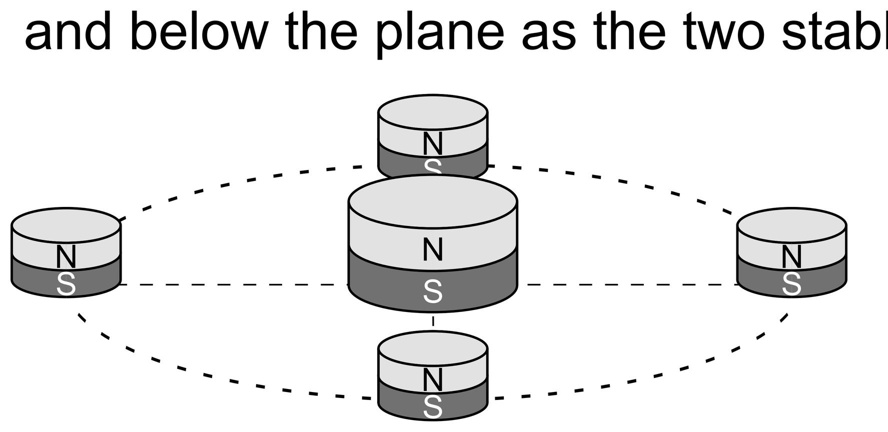
Objective

This research develops a multi-stable chain of interconnected bistable links that utilizes extremely low frequency excitations from its environment to cause individual snap through dynamics between links. These impulses are transmitted along the chain in a cascading effect resulting in higher frequency vibrations that can be converted to electrical energy via electromagnetic induction.

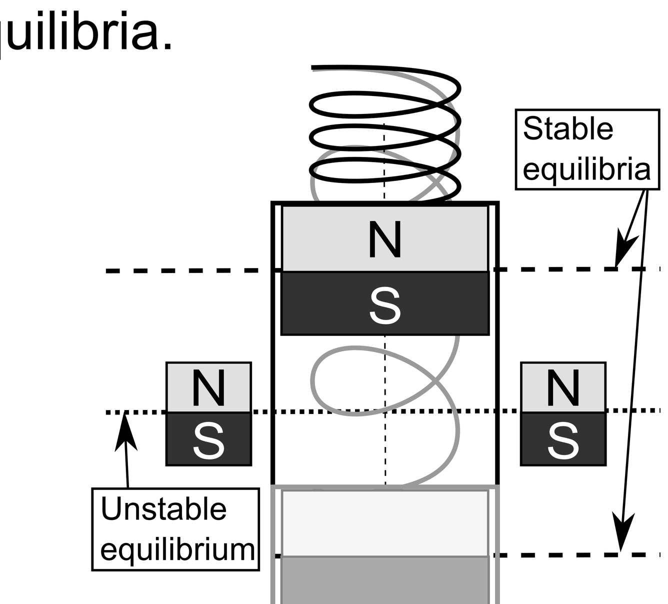
Development

A bistable system enables two positions of stable equilibrium separated by an unstable equilibrium position. This is exemplified by the double-well potential energy profile. In the design, bistability is achieved between links by the combination of magnets and a linear spring. Four outer magnets are radially and symmetrically placed around a central magnet, which is suspended by a spring. The center magnet is offset from the plane of the outer magnets by way of selection of polarity. The linear spring stabilizes two positions above and below the plane as the two stable equilibria.



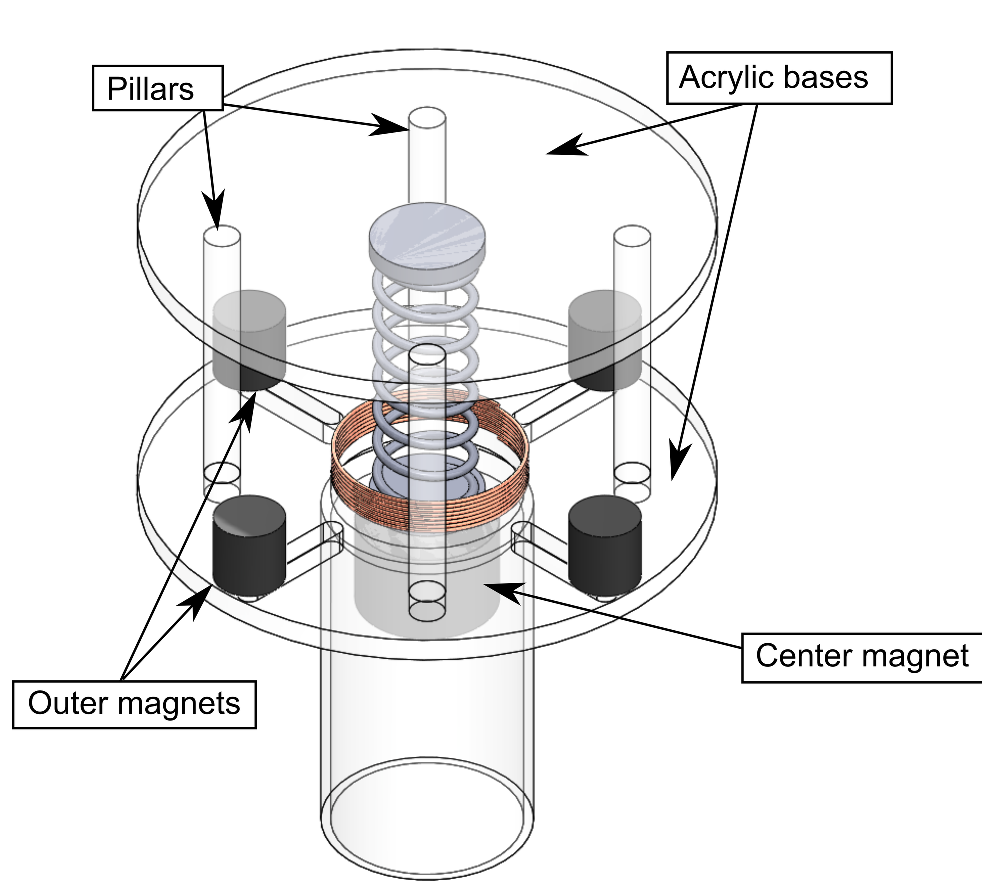


Radial positioning of center and outer magnets

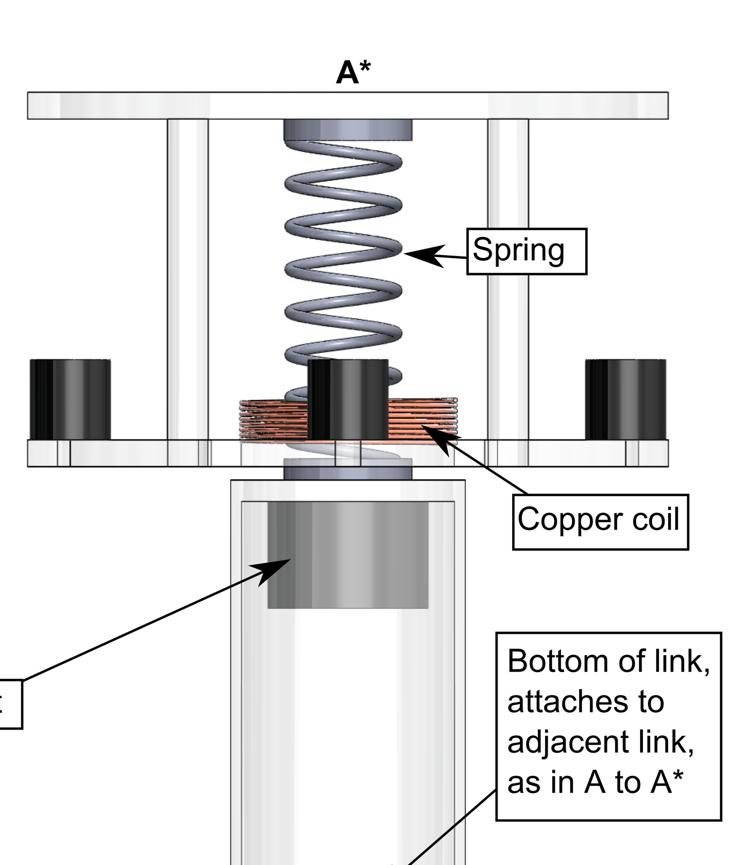


Cross-sectional schematic of two possible bistable positions with magnet polarities indicated

The linear spring also transmits snap through impulses along the chain, maximizing the amount of relative vibration induced in consequence to an individual link's impulses. Electromagnetic induction of the center magnet through a fixed coil generates electrical current collected in an external circuit.



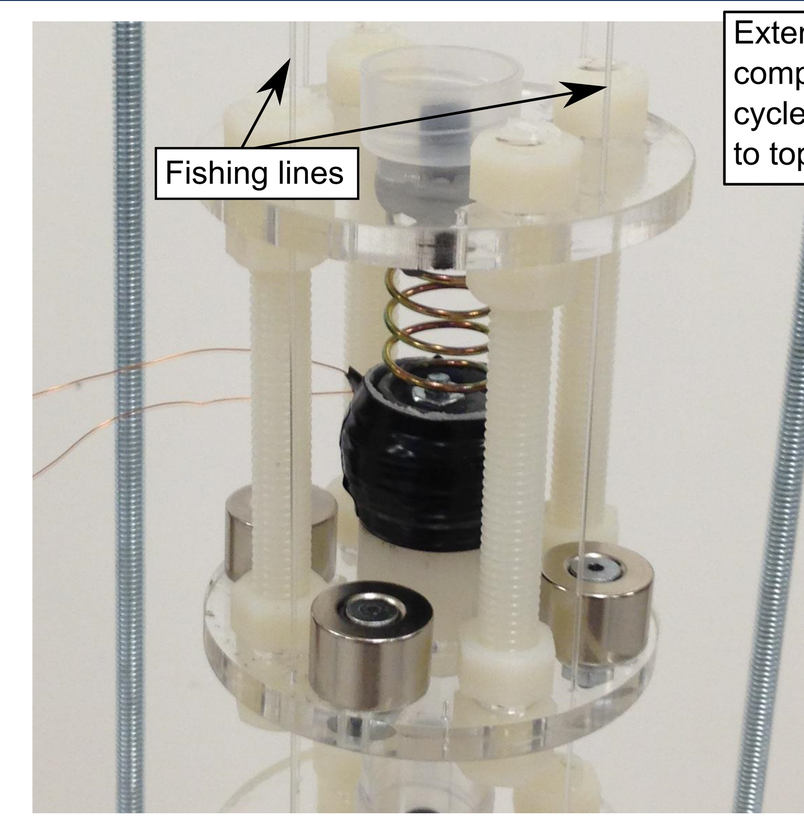
Bistable link

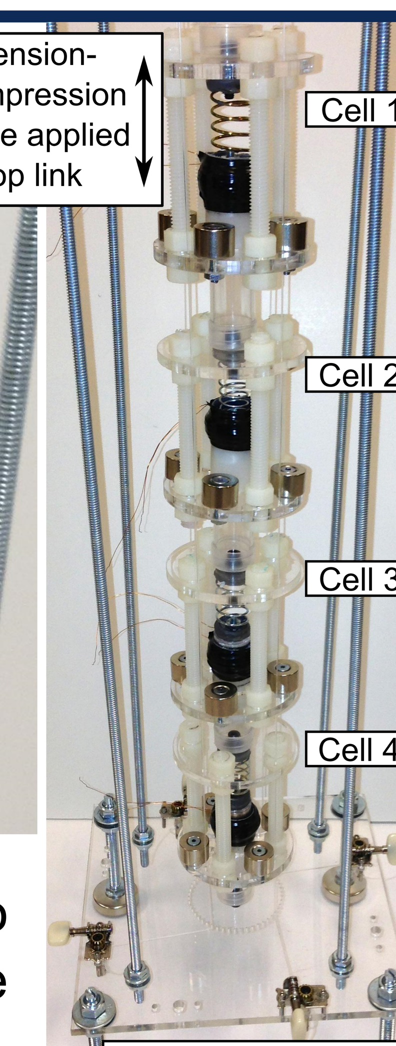


Bistable link, cross-section

Challenges

Cumulative weight effects may inhibit bistability between links. A different spring stiffness was selected for each link such that stiffer springs were used on links supporting more weight. Acrylic was chosen as the primary structural material. To constrain the system to uni-axial motion in the up-down direction like wave heaves, fishing lines guided the chain of links.

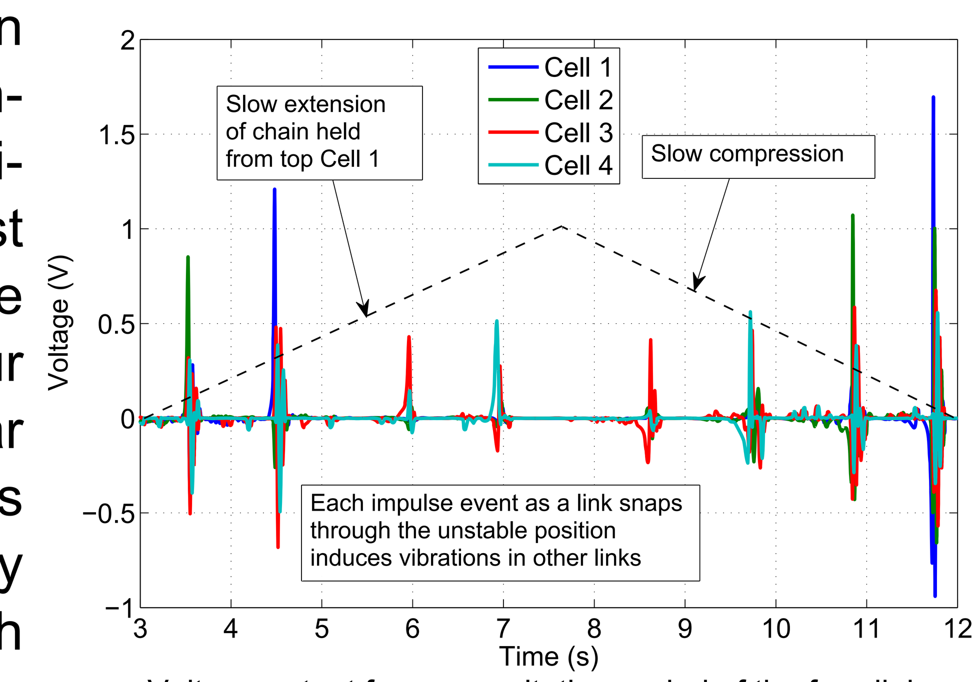




4-link multi-stable chain and test station

Testing and Results

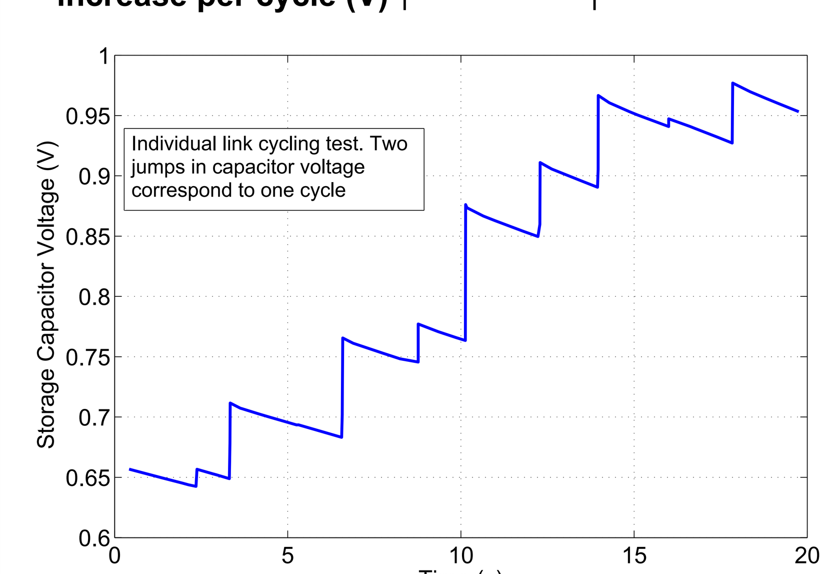
The induced electrical signals from a four-link chain were measured individually and combined in series to charge a storage capacitor. Controlled displacement excitation was manually applied to the top link to replicate slow up-down wave motion. The same procedure was carried out on one link. Progressive snap through impulses were induced in the four-link chain due to the slow extension-compression cycle. The multi-stable chain generated almost 300% of the voltage per cycle theoretically possible from four individual links at similar excitation periods, Table 1. This demonstrates increased energy harvesting performance through chain internal dynamics.



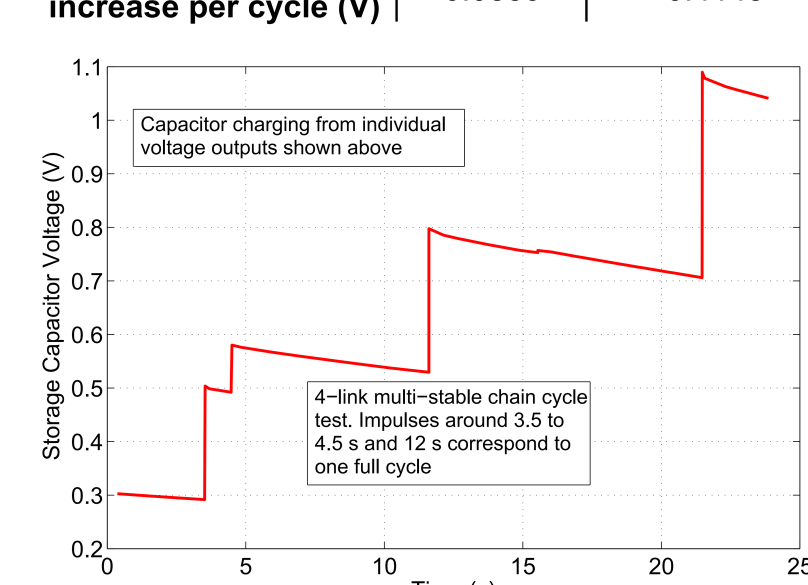
Voltage output for one excitation period of the four-link multi-stable chain

Table 1	Single link	Four-link chain
Mean cycle period (s)	1.826	2.115
Mean voltage increase per cycle (V)	0.0859	1.023

Table 2	Single link	Four-link chain
Mean cycle period (s)	1.826	8.060
Mean voltage increase per cycle (V)	0.0859	0.4145



Capacitor voltage storage for a mean testing cycle of 2.115 seconds for one single link



Capacitor voltage storage for a mean testing cycle of 8.060 seconds for the four-link chain

The multi-stable chain output approximately 20% more voltage per cycle than the amount theoretically possible from four individual links for an excitation period of 8.06 seconds, compared to 1.86 seconds for the individual links, Table 2. The multi-stable chain effectively converts large displacement and long period excitations common to wave environments into usable electrical energy.

Conclusions

A multi-stable chain was developed to provide new opportunities for mobile marine power supplies. As the chain is slowly extended and compressed similar to a wave motion, the coupling of links along the chain creates a cascading effect as individual links cross unstable positions and transmit impulsive vibrations to neighboring links. Energy harvesting performance is greatly improved as compared to individual, isolated links. Future work will focus on system optimization and address feasibility questions.