Nearly all military operations require remote power. For instance, consider the modern soldier who has been equipped with an increasingly sophisticated array of sensing, communications, and related electronics. While batteries have historically been used to power these electronics, alternative solutions are now required since a significant number of batteries, along with their increased weight, must be carried to meet the power requirements of short-term missions. Scavenging energy from the ambient environment, to either replace or recharge batteries, is one of the most promising strategies for meeting the power requirements while simultaneously reducing the weight.
ABSTRACT

Nearly all military operations require remote power. For instance, consider the modern soldier who has been equipped with an increasingly sophisticated array of sensing, communications, and related electronics. While batteries have historically been used to power these electronics, alternative solutions are now required since a significant number of batteries, along with their increased weight, must be carried to meet the power requirements of short-term missions. Scavenging energy from the ambient environment, to either replace or recharge batteries, is one of the most promising strategies for meeting the power requirements while simultaneously reducing the weight load. However, energy harvesting has yet to reach its full potential because the past works have narrowly focused on frequency matching to achieve linear resonance.

To summarize, the current state of the art in mechanical energy harvesting is ineffective for many environments. The proposed research explores new concepts with the potential to offer fundamentally new insights for energy harvesting. I expect this project to provide enabling technological advancements, with outcomes that are applicable to numerous defense applications, while simultaneously providing general scientific insights targeted to supplant the current design paradigms.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received: 

Paper: 

TOTAL: 

Number of Papers published in peer-reviewed journals: 

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received: 

Paper: 

TOTAL: 

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Detailed listing of publications is given in an attached document
Number of Presentations: 0.00

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**TOTAL:**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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**TOTAL:**

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**TOTAL:**

(d) Manuscripts

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**TOTAL:**
Awards

• Philip E Doak Award - Journal of Sound and Vibration. Awarded for the most cited journal article over a four year period.

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• Invited to give a plenary lecture on the topic of Nonlinear Energy Harvesting at the 2012 ASME SMASIS conference.


Graduate Students

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<td>Brian Bernard</td>
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FTE Equivalent: 0.25
Total Number: 1

Names of Post Doctorates

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FTE Equivalent: 0.00
Total Number: 0.00

Names of Faculty Supported

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FTE Equivalent: 0.10
Total Number: 1

Names of Under Graduate students supported

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FTE Equivalent: 0.00
Total Number: 0.00

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields: 0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields: 1.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): 1.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: 0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense: 0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

<table>
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<th>NAME</th>
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Total Number: 0.00
In contrast to the current state of the art, my research investigated using highly nonlinear interactions to obtain a more broadband response and to enable semi-active tuning. For instance, I will investigate different types of nonlinear restoring forces, both smooth and non-smooth forces, to adapt and/or tune the harvester's response to the environmental excitation, e.g. to trigger attractor escapes and/or the system to jump to a more energetic response. The general idea is to destabilize the local attractor, while keeping the global dynamics bounded, to harvest energy from the oscillations of a system that is transitioning between multiple states of equilibria. Since any nonlinear harvester can have multiple (co-existing) steady-state behaviors, I will investigate the selection of the desired response (attractor selection) from a momentary feedback perturbation; this idea, in contrast to a consistent control effort, which continuously dissipates energy, only perturbs the system once to trigger an attractor escape and cause the system to jump to a more energetic response indefinitely.

The final research phase explored a new concept where nonlinearity could be exploited in a beneficial fashion. More specifically, the creation of bandgap structures that passively reconfigure, in a prescribed manner, can provide enabling capability, e.g. the ability avoid damage in many structures. This threshold-triggered (or passively switched) type of response behavior would allow energy to be passed in a frequency band until the bifurcation parameter reached a critical value; once the bifurcation parameter exceeds this threshold, the bandgap structure would then reconfigure to attenuate energy propagation over a desired frequency range. In essence, the bifurcation point, bandpass, and bandgap regions must be simultaneously designed to achieve the aforementioned phenomenon (see Attachment for further details).

**Technology Transfer**

We have worked with program director Samuel Stanton to identify an ARL research group with compatible interest. A student on this project, Ben Owens, interviewed with this group at Redstone Arsenal and was hired for the summer of 2012 at AMRDEC.
Nonlinear Interactions for Broadband Energy Harvesting

A progress report submitted to:

Army Research Office

Program Officer: Dr. Ralph Anthenien
Research Area: Mechanical Sciences
Subcategory: Structures and Dynamics

by

Principal Investigator

Brian Mann
Associate Professor
MEMS Department
238 Hudson Hall
Duke University
Durham, NC 27708
Tel: 919-660-5214
Email: brian.mann@duke.edu
Summary

Nearly all military operations require remote power. For instance, consider the modern soldier who has been equipped with an increasingly sophisticated array of sensing, communications, and related electronics. While batteries have historically been used to power these electronics, alternative solutions are now required since a significant number of batteries, along with their increased weight, must be carried to meet the power requirements of short-term missions. Scavenging energy from the ambient environment, to either replace or recharge batteries, is one of the most promising strategies for meeting the power requirements while simultaneously reducing the weight load. However, energy harvesting has yet to reach its full potential because the past works have narrowly focused on frequency matching to achieve linear resonance.

To summarize, the current state of the art in mechanical energy harvesting is ineffective for many environments. The proposed research explores new concepts with the potential to offer fundamentally new insights for energy harvesting. I expect this project to provide enabling technological advancements, with outcomes that are applicable to numerous defense applications, while simultaneously providing general scientific insights targeted to supplant the current design paradigms.

In contrast to the current state of the art, I propose to use highly nonlinear interactions to obtain a more broadband response and to enable semi-active tuning. For instance, I will investigate different types of nonlinear restoring forces, both smooth and non-smooth forces, to adapt and/or tune the harvester’s response to the environmental excitation, e.g. to trigger attractor escapes and/or the system to jump to a more energetic response. The general idea is to destabilize the local attractor, while keeping the global dynamics bounded, to harvest energy from the oscillations of a system that is transitioning between multiple states of equilibria. Since any nonlinear harvester can have multiple (co-existing) steady-state behaviors, I will investigate the selection of the desired response (attractor selection) from a momentary feedback perturbation; this idea, in contrast to a consistent control effort, which continuously dissipates energy, only perturbs the system once to trigger an attractor escape and cause the system to jump to a more energetic response indefinitely.

Research Progress

Amplitude Filtering Through Bifurcation Induced Bandgap Changes - This task explored a new concept where nonlinearity could be exploited in a beneficial fashion. More specifically, the creation of bandgap structures that passively reconfigure, in a prescribed manner, can provide enabling capability, e.g. the ability avoid damage in many structures. This threshold-triggered (or passively switched) type of response behavior would allow energy to be passed in a frequency band until the bifurcation parameter reached a critical value; once the bifurcation parameter exceeds this threshold, the bandgap structure would then reconfigure to attenuate energy propagation over a desired frequency range. In essence, the bifurcation point, bandpass, and bandgap regions must be simultaneously designed to achieve the aforementioned phenomenon, as shown in the example case study below.

While we expect to explore numerous magnetic lattices arrangements with bandgap structures that can passively reconfigure, the present discussion will focus on the example of Fig. 1. This system
has two masses in a unit cell, linear interconnections (assumed for simplicity, but not required), and a nonlinear restoring force for every other oscillator. Mathematically, this system can be described by the following two equations:

\[
m_j \ddot{x}_j + d \dot{x}_j + k (2x_j - x_{j+1} - x_{j-1}) = 0 \quad \forall \quad j = 1, 3, 5, \ldots , \tag{1a}
\]
\[
m_j \ddot{x}_j + d \dot{x}_j + k (2x_j - x_{j+1} - x_{j-1}) - ax_j + bx_j^2 + cx_j^3 = 0 \quad \forall \quad j = 2, 4, 6, \ldots , \tag{1b}
\]

where the constants \(a\)–\(c\) describe the nonlinear restoring force. Here, it is important to note that the coefficients of the restoring force model are related to several magnet parameters.

![Figure 1](image-url)

**Figure 1:** Schematic diagram of a unit cell (a) comprised of two masses in an alternating pattern of a bistable (b) and monostable (c) oscillator. A bifurcation in the response of this system can be used to realize a different bandgap structure than the one found in the adjacent potential well - particularly when \(b \neq 0\). Frequency band graphs show: (d) the symmetric case, where \(b = 0\), and identical frequency band structures occur for each equilibria; (e) an asymmetric case, where \(b \neq 0\), highlighting the pre-bifurcation bandpass region can be tailored to become a post-bifurcation bandgap region by tuning the parameter \(b\).

To explain the behavior of this system, first consider the case of a symmetric potential, which requires \(b = 0\) in Eq. (1b). After solving the nonlinear algebraic equations to find the system equilibria and expanding for small oscillations about the nonlinear equilibria, we solved for the frequency band structure that yields the bandgap region shown in Fig. 1(d); while Fig. 1(d) shows a bandgap occurs, the bandgap is identical for oscillations about either stable equilibria of the blue oscillator in Fig. 1(a). Similarly, one could say the bandgap structure is identical for the adjacent potential well owing to symmetry. In contrast to this case, consider what happens when symmetry is broken or equivalently when \(b \neq 0\); the frequency band structure of Fig. 1(e) shows the bandgap regions for the adjacent well no longer coincide. This different bandgap structure is an important feature because a transition from one equilibria to another will shift the bandpass and filtered (or bandgap) regions by an amount proportional to the parameter \(b\). However, a bifurcation is required to transition the oscillations about one stable equilibrium to oscillations about the neighboring stable equilibrium. For this example, we have used numerical simulations to demonstrate
how the threshold for an escape from the shallower potential well (the 4-4.75 Hz bandgap region shown by the solid blue lines of Fig. 1e) can be used to transition the system to the deeper well (bandgap region shown by broken red lines of Fig. 1e) and quench the oscillation amplitude. This occurs only because the bandpass region of the shallower well was aligned with the bandgap region of the neighboring well. To summarize, successful demonstration of this concept will require simultaneous tailoring of the bifurcation transition and the bandgap structure.

This past year my group worked on both theoretically studying this phenomenon and developing an experimental system to demonstrate this behavior. Two papers were published on this topic - the first two references from the Journal Publications sections of this document. Basically, my group was successful in developing an experimental platform to demonstrate the phenomenon.

Students Supported

The students listed below have contributed to the research endeavors of this project:

- Brian Bernard, received a PhD in Aug 2014 and was supported by this project.
- Benjamin Owens, received a PhD in Aug 2014 and was supported by this project.
- Samuel Stanton, received a PhD in Mar 2011, was supported by a one year fellowship during his last year, but worked on several topics akin to the direction of the proposed research.

Past Interactions with ARL Researchers

We have worked with program director Samuel Stanton to identify an ARL research group with compatible interest. A student on this project, Ben Owens, interviewed with this group at Redstone Arsenal and was hired for the summer of 2012 at AMRDEC.
Honors

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Journal Publications


**Conference Publications**


Conference Abstracts

Select Technical Presentations


4. Mann, B.,P., “Opportunities for fundamental advancements in energy harvesting,” ARO Workshop on revolutionary research in energy harvesting, Austin, TX, April 7, 2011.