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Developing Innovative Energy Harvesting Approaches for Infrastructure Health Monitoring Systems

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ABSTRACT

Many factors must be addressed when designing infrastructure health monitoring systems. Structures in remote locations or with limited accessibility make the requirements for these systems unique and challenging. For locations where connection to the power grid is difficult or impossible, monitoring system life is severely limited by battery technology. Alternatively, an energy harvesting power supply can make the monitoring system independent of the grid while increasing capabilities and lifetime beyond what is possible with current battery technology. This paper discusses a design and development methodology for developing energy harvesting aspects of a health monitoring system. The system comprises a sensor module that monitors the health of the structure, an on-site processing module that analyzes the data, and a wireless communication module that transmits the data. The method is demonstrated by examples of energy harvesting systems for a bridge monitoring application, using solar, wind, and vibration energy harvesters to provide power to a wireless network, local data processors, and strain gauges. Theoretical feasibility of energy harvesting in these domains has been previously demonstrated. The examples described in this paper validate the feasibility previously calculated as well as illustrate shortcomings in the current technology that inhibit potential implementation. The examples also show areas where innovation is needed to continue to advance the technology of energy harvesting in this application on infrastructure.

1. INTRODUCTION

As anything ages, it requires maintenance and eventual replacement; the infrastructure used by the American people is no different. Much of the infrastructure in the United States is beginning to come to the end of its design life, and some are even pushing beyond that life [1]. Inspecting these structures is expensive, time consuming, and difficult. [2]

1.1 BACKGROUND

Bridges are an example infrastructure with aging members that are difficult, time consuming, and expensive to inspect [5-7]. Currently, visual inspections of cracks on a bridge are scheduled based on age and previous condition of the bridge. Performing this inspection is difficult due to the need to reroute traffic, use of specialized vehicles, special training of inspectors, and the environments bridges span. Of a population of 200,000-400,000 bridges in the United States, a reported 70,000 have been labeled in critical condition. With the collapse of the IH-35 bridge in Minnesota, the public's attention has been drawn to the danger posed by failing bridges [8].

As a potential solution to current inspection difficulties, wireless sensor nodes are being developed for bridge application. A key issue involved in this development is the method of powering the nodes across all bridge types and locations. Harvesting energy from the environment is identified as a potential solution to powering the sensor and wireless network [27]. Harvesting can potentially lengthen the life cycle of a system, decreasing maintenance and costs. Many requirements, constraints, and design variables must be addressed when developing an energy harvesting system. The following paper presents a methodology to produce an energy harvesting system to power monitoring sensors and a wireless communication network.

1.2 APPLICATION

For clarity, the application addressed in this paper will be placing sensors on bridges to monitor health of the girder structures. The sensors are potentially located in places where accessibility is limited, costly, or unsafe. Under the bridge deck, inside girders, and in the middle of a span are examples of such locations. Minimizing wiring is a way to make the system cost effective and viable in remote locations, but this also requires an independent power source. A target of 10 years without maintenance is proposed, which currently exceeds present battery technology capabilities. Energy harvesting has been identified as a feasible alternative [27].

1.3 MOTIVATION

Developing an energy harvesting system must investigate and take into account many different parameters, including but not limited to, determining power requirements, power densities, variability, storage, mounting, and safety of the system and the surroundings. In addition to the many engineering requirements, constraints, and design variables, there exists other issues which must be solved for a long life monitoring system. The conditions found in a bridge setting challenge the design to take into account problems with debris, wildlife, location, aesthetics, and vandalism. This paper introduces a methodology to guide the development of energy harvesters to be used in a health monitoring wireless system.

2. ENERGY HARVESTING DESIGN METHODOLOGY

This paper discusses a methodology for developing energy harvesting aspects of a wireless health monitoring system. The system comprises a sensor module that monitors the health of the structure, an on-site processing module that analyzes the data, and a wireless communication module that transmits the data. The method is demonstrated by examples of energy harvesting systems for a bridge monitoring application, using solar, wind, and vibration energy harvesters to provide power to a wireless network and strain gauges.

Theoretical feasibility of energy harvesting in these domains has been previously demonstrated [27]. The examples described show how the methodology aids in the development of a concept. The conceptual designs illustrate where areas of innovation were pursued. The proofs of those concepts demonstrate the system, their innovations, and where innovation needs to continue to advance the technology of energy harvesting in this application on infrastructure.

The methodology used in this paper is available in Figure 1. The first step is assessing the power requirements of the sensors and wireless network that needs powering. The second step involves characterizing the structure, and where the different components will be located (i.e. under the bridge, between the girders, etc.). This step will provide parameters necessary when designing the mounting and housing of the system. The third step involves analyzing the environment that surrounds the structure. The fourth step is choosing an energy harvesting technology. The fifth step is determining the variability in the energy being harvested. The sixth step is calculating the level of energy storage that is going to be required. The seventh is developing innovative concepts and mapping chosen concepts into viable realizations through, e.g., off the shelf components that will fulfill the requirements while working together. The eighth step is to combine these components, and fabricate any supporting component unavailable commercially. The final step is to assemble the system and perform systematic testing. A more detailed description of each step can be found below.

Step 1: Assessing the Power Requirements of the monitoring system

The power requirements of the monitoring system involve many different factors, e.g., determining the power requirements of the sensors and the communication network, and the duty cycle. Minimizing the power requirements of the different components of the system will aid in creating energy harvesting alternatives that are viable and advance the state-of-the-art. Exploring energy saving methods, such as sleep modes, is important when developing the sensors and communication networks, but inevitably the system will require power [27]. Identifying these factors will allow first the feasibility of energy harvesting to be determined, and then give vital design parameters.

Step 2: Characterize the Structure

Characterizing the structure is essential when determining the available power, and how it can be harvested, adding important technical scope and constraints to the different systems. This step involves gathering raw data about the structure, from vibration history and natural frequency, to typical wind speed and wind profile, to insolation and angle of incidence of the sun's rays, among others. Analysis of this data will provide many important design parameters, requirements, and constraints for the energy harvester. In addition, mapping the geometry of the bridge, and the surrounding environment will be determined during this step. Information such as traffic patterns that passes beneath the bridge, or environmental conditions such as waterway flow, will need to be noted because this will add a height requirement to any system that hangs below the bridge. Any points eligible for attachment should be identified during this stage. Data acquisition and analysis will be discussed further later in the paper in more application specific sections.

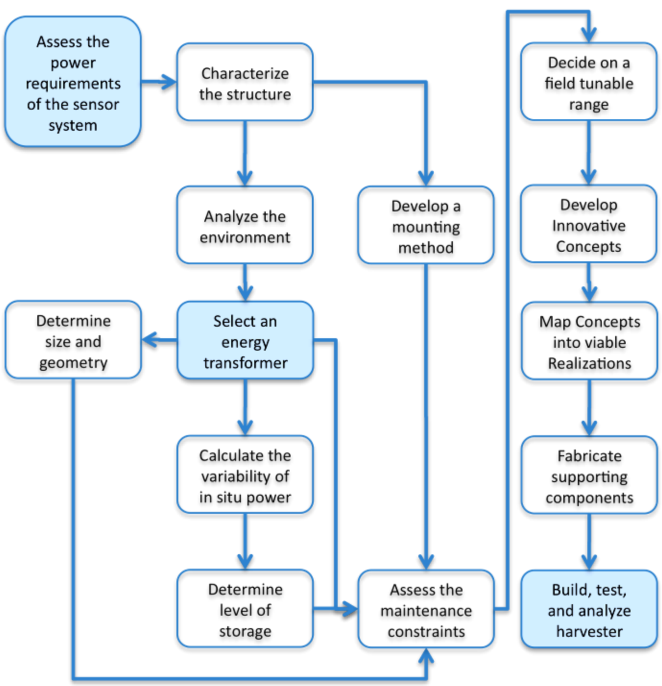

Figure 1. Energy harvesting development methodology.

Step 3: Analyze the Environment

The characterization of the structure is represents a snap shot of what energy is available for the harvester, and the condition it will need to survive. Collecting long-term data is expensive, personnel and time intensive, and can become overwhelming. Instead, the characterization should be compared to data from a wider window of time. Traffic (type and frequency) and weather patterns (seasonal and yearly) provide adequate data volume and time span to develop suitable models, and are essential for this analysis and determining the design parameters for the system.

Research into the wildlife and the potential for vandalism should be carried out at this point as well. Preventing wildlife disruption and intrusion is important for the safety of the environment as well as the energy harvester. Preventing crime, such as theft, is another problem that needs to be addressed.

Step 4: Select a Transformer

Selection of a transformer is determined by the structure, environment, and component (power requirements). Balancing feasibility and cost will be the driving forces in this decision, but several alternatives may be viable depending on power requirements. Sun harvesting will have the highest power and energy density, followed by wind, and vibration [27]; however, these rankings have tradeoffs associated with them. For instance, sun harvesting also has the most constraints, is difficult to blend or hide with the bridge environment, and is most likely to be vandalized. Often, a combination of multiple harvesting domains, at least within a portfolio of designs or as hybrid solutions, will be the most beneficial to any system.

Step 5: Develop a Field Tunable Range

The design parameters determined by data analysis will result in a system unique to the designer's choices. In the field, not every condition is going to be the same; different locations on the bridge may even differ. Having a tunable range or tuning parameters will increase the utility of the harvesting system [46]. A field technician would be capable of adjusting the harvester for maximum effectiveness. In addition, if the harvester is designed to tune autonomously to account for varying conditions, it may always operate near optimally. The mounting sub-system is another area where tuning will be crucial in an effective design.

Step 6: Calculate the Variability of In Situ Power

Independence of the entire system is one of the major requirements, making a power failure unacceptable. Statistical analysis of the variability in harvesting energy is important to prevent power failure. Appropriate power storage, and power storing methods will be determined according to the results of the model. The customer and design team should jointly analyze an acceptable probability of success

Step 7: Develop Innovative Concepts and Map to Viable Solutions

Energy harvesting represents a technological challenge. Available energy and power densities make energy harvesting a difficult and non-trivial design problem. While energy harvesting for infrastructure health monitoring requires modest or lower power levels, innovative solutions are needed that efficiently and effectively capture, store, and supply energy. In the context of steps 1-6, a first sub-step toward such innovations is the ideation of inventive energy harvesting concepts.

A number of ideation methods may be deployed in generating inventive concepts. These include brainstorming combined with mind mapping, C-Sktech or the 6-3-5 method, design-by-analogy, and transformational design [43-45]. Figure 2 shows exemplar results of ideation methods applied to the energy harvesting problem for bridge monitoring.

Figure 2. Mind Map Results from Brainstorming.

Following the ideation and selection of innovative concepts for energy harvesting, chosen concepts are embodied, architected, and mapped to viable form solutions. Many of the technologies that are used in an energy harvester are available commercially. Commercial products have the advantage of reduced losses because the companies that sell them have perfected mass production. Finding commercial products will also decrease build time. It is important to select compatible components because compatibility is essential to creating an efficient system. Incompatibilities will result in losses that could result in an unsuccessful system.

Step 8: Fabricate supporting components

The final key step before assembling and systematically testing the energy harvester is to fabricate the necessary supporting components. Some examples of these would be couplers from the rotor of the fin to the rotor of a wind generator. Careful planning during this step will decrease unnecessary and hindering losses in the system.

3. ENERGY HARVESTING EXAMPLES

To demonstrate the methodology's value when developing energy harvesters for the bridge application previously described, three example harvesters are developed. The steps in the methodology are described in sections according to the input harvesting energy. Step 1 was used by all the harvesters, and therefore just described once. Steps 7 and 8 offer a discussion on the concepts produced from the methodology followed by a proof of concept for each example.

3.1 ASSESS THE POWER REQUIREMENTS

The exemplary bridge application is typically powered by a 6 V battery, and operates on a 1 second sample interval [5]. Figure 3 shows a plot of this interval, and Table 1 breaks the power draws down into activities.

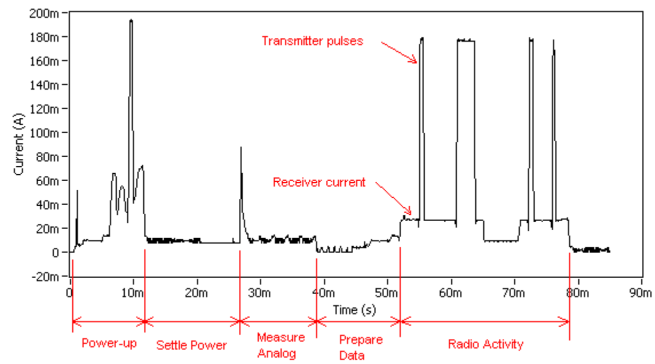

Figure 3. Waveform of power consumption during sampling.

Table 1. Break-down of power consumption.

Function	**Power (mW)**	**Δt (ms)**
Power-up	200	12.4
Settle power	52.5	14.5
Measure analog	73.4	13.0
Prepare data	37.9	12.0
Radio activity	207	29.0
Total – active period	154 (average)	81
Sleep period	0.3	variable

Solar has been shown to be feasible, and is common in many similar applications such as emergency phones [27]. In the previous feasibility study, a photovoltaic panel of 1000 cm^2 would be capable of powering the system [27]. Betz's law describes the available power from wind as a function of wind speed, and swept area. The previous feasibility study has shown that theoretically a small turbine (1 cm^2 swept area) would be capable of powering the low power components, and a slightly larger turbine (92 cm^2 swept area) would be capable of powering the high power component [27]. Therefore, the feasibility of harvesting wind energy was determined to be valid. Vibration feasibility has been previously calculated, and was demonstrated by Clarkson University using inductive technology [20]. The vibration feasibility has a lower density, and therefore would be used to power the low-power consuming components [27].

3.2 CHARACTERIZE THE STRUCTURE

Wind data and vibration data for the bridge was collected during field testing. Section 3.2.1 describes the wind data collection and analysis, and Section 3.2.2 describes the vibration collection and analysis for the example bridge. The field test was conducted on a bridge where Loop 410 and IH-35 intersect in San Antonio.

3.2.1 CHARACTERIZE THE STRUCTURE: WIND

To characterize the wind at the structure, wind data was collected on site at multiple locations. The selected bridge had traffic that passed under it, and so no system could hang below the bottom flange. Anemometers were utilized to collect data at multiple points beginning at the bottom flange, and rising into the structure to give a profile of flow above the bottom of the bridge. Figure 4 shows a plot of the average wind speed at three heights within the structure.

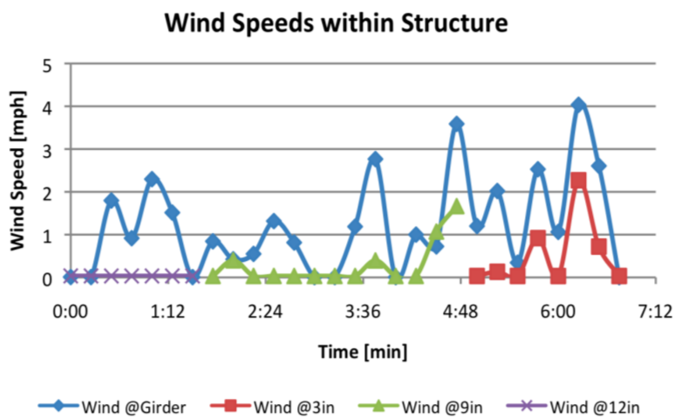

Figure 4. Wind Speed within structure vs. time.

Analysis of the data showed the majority of the wind energy is concentrated at and just above the bottom flange. Also, the wind has turbulent characteristics due to obstructions affecting the flow. Lastly, attachment points of interest were investigated during the field study. First, the system's mounting may not require modification of the structure, disqualifying bolting or welding anything to the structure. The flange, and cross frame were both available and viable attachment points. Figure 5 shows an example of the I-girders and cross frame.

At the conclusion of the characterization, the following design considerations were documented:

- System may not hang below structure
- Energy is concentrated very close to the bottom of the structure
- Turbulent flow
- Low wind speeds
- Flange and cross frame offer viable attachment points.

3.2.2 CHARACTERIZE THE STRUCTURE: VIBRATION

Highway bridges are typically I-girder, box-girder, or truss structures. An example I-girder bridge was shown in Figure 5 and an example box-girder bridge is shown in Figure 6. To assess bridge vibration amplitude and frequency accelerometers were placed on the girders of two local I-girder bridges and one local box-girder bridge for two weeks. Each bridge was found to vibrate over different frequency ranges. The box-girder bridge which is relatively stiff was dominated by 1-7 Hz vibrations, while the shorter I-girder bridge occupied the 10-21 Hz range. The longer I-girder bridge was a half-century older and vibrated between 1-19 Hz. The vibration frequencies also changed with location on the bridge, as shown in Figure 7, which gives power spectrums of five locations along a single span of the box-girder bridge.

The acceleration amplitude also depended upon location along the bridge, with a maximum at mid-span. Figure 8 shows the peak accelerations of the box-girder bridge over an interval of five hours. The amplitude levels were similar for the three bridges instrumented. As expected, lower amplitudes occurred near the supports, with the exception of the abutment, which is due to vehicles impacting an expansion joint as they enter the bridge. Highest amplitude was measured in the middle of the first span, as expected, but high damping from the second support, which differs from the first, limited vibration in the second span.

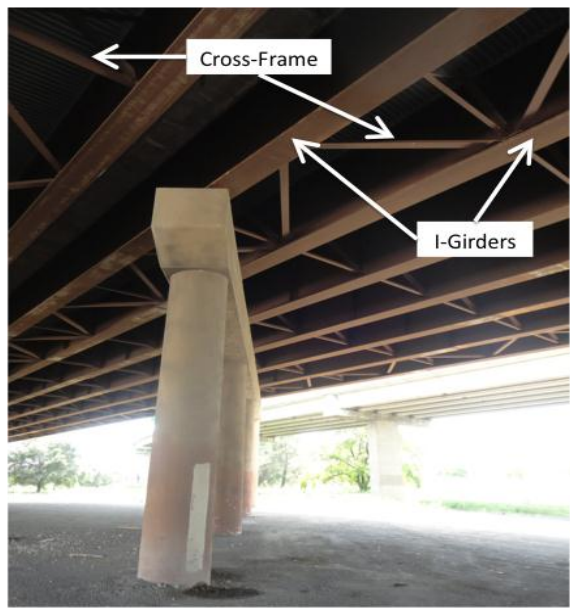

Figure 5. Cross-frame and I-girders.

3.3 ANALYZE THE ENVIRONMENT

Analysis of the wind and vibration environments was conducted, and is described in Sections 3.3.1 and 3.3.2 respectively. The wind analysis occurred on the bridge in San Antonio; in addition, vibration analysis was also done on a box girder bridge in Austin, TX. Analyzing the environment offered additional information, which is noted below, increasing the design considerations and understanding.

3.3.1 ANALYZE THE ENVIRONMENT: WIND

When analyzing the data, the low wind speeds were an immediate concern. Betz's law states that the available power is affected by the cubic of wind speed, making this parameter very important to the design [28]. A comparison was conducted of the wind speed found during the characterization and the typical wind conditions. Two aspects were researched: the average wind speed for that location [29], and the wind speeds for the same time as the data acquisition [30]. Figure 9 shows a plot of the data gathered versus the average wind speed for San Antonio and the wind speed at different times for the same day.

Analysis of this information gives many insights into design parameters and constraints. First, the average wind speed in San Antonio is faster than the recorded data from the weather stations, which was faster than data acquired at the bridge. This information concludes that although the wind is slower at the bridge, it will be on average faster than on the day the data was collected, and gives insights into the variability of wind speeds. Design considerations drawn from these conclusions are as follows:

- Wind speed is going to be lower at the structure
- Potential for large variation in wind distribution

Figure 6. Inspection of the underside of a typical box-girder bridge.

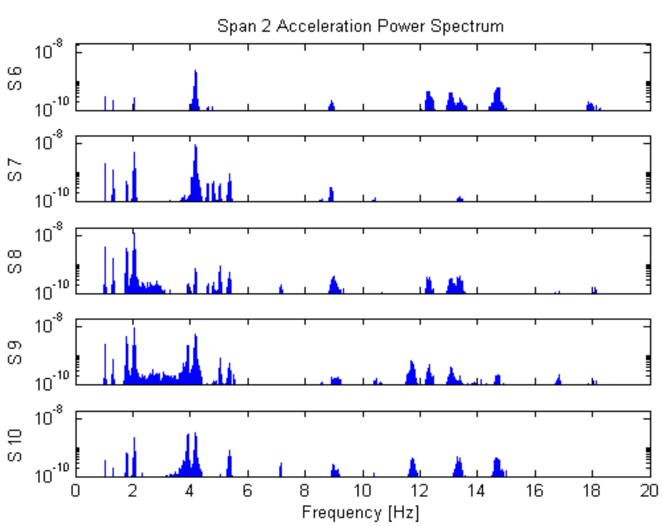

Figure 7. Power spectrums of five locations along box-girder bridge span with sensors 6 and 10 near supports and sensor 8 at mid-span.

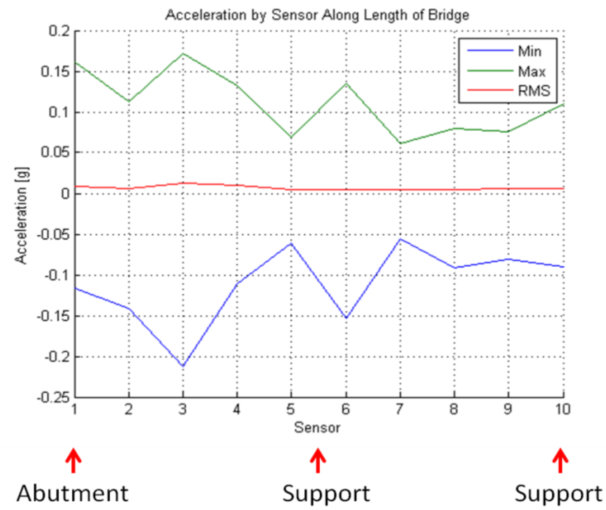

Figure 8. Acceleration amplitudes of ten locations along two spans of a local box-girder bridge.

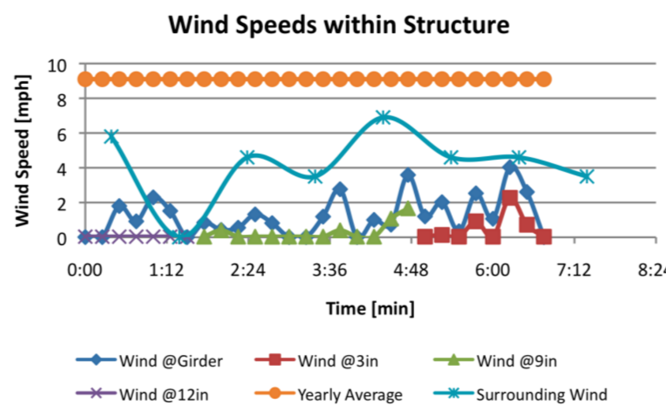

Figure 9. Comparison of Wind Speeds.

3.3.2 ANALYZE THE ENVIRONMENT: VIBRATION

The source of the bridge vibration is heavy vehicle traffic such as trucks and buses, which indicates some dependence on the amount of traffic and speed. These indications rapidly increase the complexity of predicting available energy for harvesting. Even so, there exist some models of bridge vibrations excited by traffic, showing vibration patterns predominantly in the 1-15 Hz range [35-37]. While recording acceleration data at the three bridges previously discussed, a log was created of heavy vehicles and the times they passed a set location on the span in attempt to associate accelerations with the traffic. One can see the resulting acceleration time series in Figure 10 from three trucks, shown as impulses followed by damped oscillation. Accelerations were recorded on each bridge with varying traffic loads with the conclusion that the weakest I-girder bridge's response was very traffic dependent while the other two stronger bridges varied only slightly from their natural frequencies.

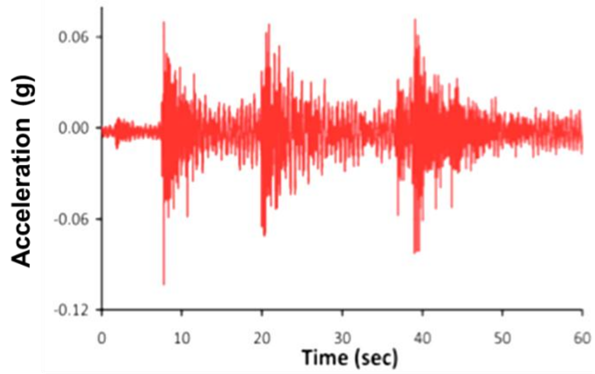

Figure 10. Bridge acceleration from three trucks during a time of relatively low traffic.

3.4 SELECT A TRANSFORMER

Characterization of the bridge was completed as previously described. The different domains were found to be feasible in powering different aspects of the bridge monitoring system. The different domains (solar, wind, and vibration) were all pursued for different components of the application. An example of wind and two vibration harvesters are described below as examples for the purposes of demonstrating the methodology. The remaining steps of the methodology are demonstrated in order and grouped according to the example.

3.5 DEVELOP A FIELD TUNABLE RANGE

3.5.1 A FIELD TUNABLE RANGE: WIND

Any harvester has a range of operation parameters; one of the concerns with wind harvesting in this application is operation below the cut in speed of conventional systems [28]. Harvesting energy at lower wind speeds became an area of concern during the design approach of this application. Concept generation addressing this specific problem was addressed during the design phase.

3.5.2 A FIELD TUNABLE RANGE: VIBRATION

The bridge vibration data shows frequency shifts with location, time, traffic, and (likely) temperature, leading to the conclusion that a well-designed vibration harvester should have a wide bandwidth, tunable resonant frequency/frequencies, or both. Wide bandwidth may be achieved by many methods, some being: high damping, arrays of harvesters, nonlinear compliance, bi-stability, hard stops, and coupled harvesters [38]. Resonant frequency may be tuned by adjusting compliance via changes in geometry, axial load, or incorporation of piezoelectric actuators, as well as by mass or center of mass location [38]. These methods may be actively controlled at the expense of requiring power, or passively. For an application where a non-engineer is likely to install the harvester and perform initial adjustment low complexity is key. Such a solution is exemplified by Mann [39] where a repelling magnet is threaded closer or further from the translating magnet to shift the resonant frequency of the harvester up or down, respectively. Simulation of this was performed for a harvester with resonant frequency of 2.2 Hz and measured magnetic stiffness of a chosen pair of magnets, with a resulting range of 0.5-5 Hz as shown in Figure 11. A greater tunable range is achievable by increasing the repelling magnet size or strength.

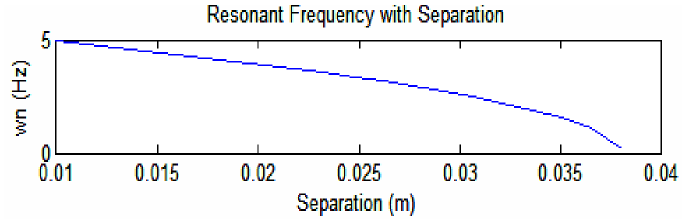

Figure 11. Resonant frequency tuning by variation of magnet separation.

3.6 CALCULATE THE VARIABILITY OF THE IN SITU POWER

3.6.1 VARIABILITY OF THE IN SITU WIND

The distribution of wind speed variability should be calculated for generator selection, and will give insights into the storage capacities required. Depending on available data, the distribution from the characterization of the structure or analysis of the environment may be used. In this example, a histogram was developed from the acquired data at the bottom of the flange, shown in Figure 12.

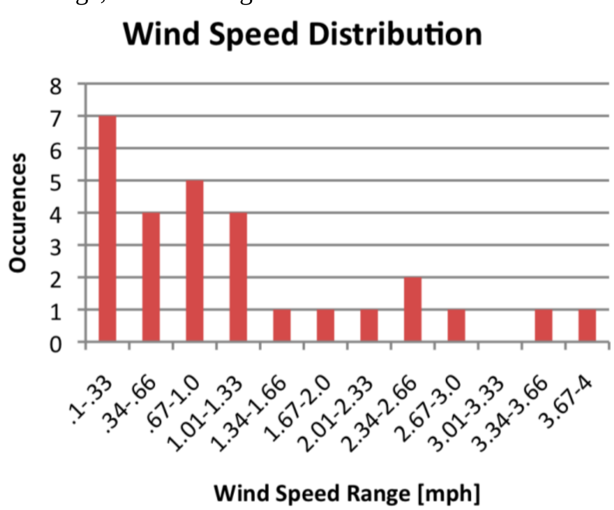

Figure 12. Distribution of wind speed at lower flange.

With the given data, a Rayleigh distribution was utilized during modeling for generator parameters and to anticipate the needed storage capacity. Additional data would make this model more accurate, and lead to better design decisions. The generator's peak operating speed was chosen to occur just above the peak Rayleigh curve value. This will transform the most energy, while protecting the generator [28].

3.6.2 VARIABILITY OF THE IN SITU VIBRATION

The dependability of vibration at specific frequencies of interest may be observed by a Spectrogram, which is a 2D intensity plot composed of a series of power spectrums over consecutive time intervals. A spectrogram of five hours of data is given in Figure 13, along with a corresponding power spectrum. In the spectrogram, red denotes highest relative power. The vertical red lines show that these frequencies do not shift with time, at least within this interval. The variability with the seasons of the year may be seen by combining spectrograms of each season. This next step is to be made upon acquisition of additional bridge data. The spectrogram also contains some thin horizontal lines due to impulses, likely from vehicles crossing expansion joints, which excited every frequency simultaneously. These impulses are much less predictable and would therefore be more difficult to harvest from, but a wide bandwidth vibration energy harvester could be designed to take advantage of their existence.

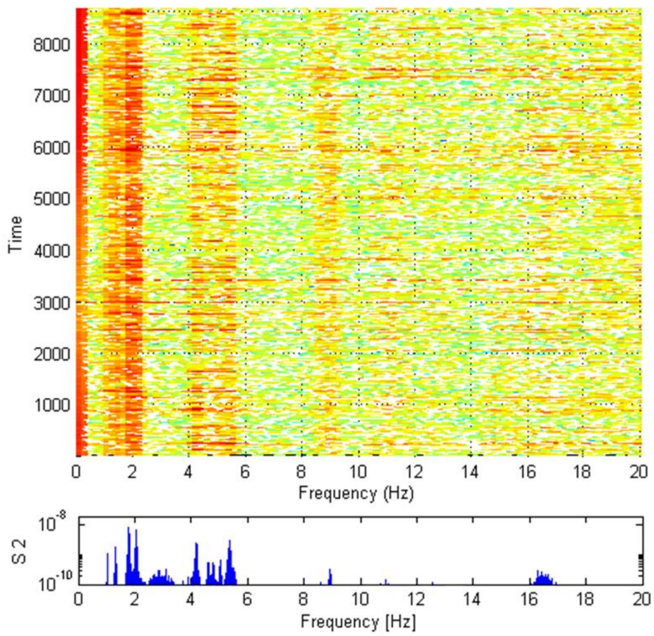

Figure 13. Spectrogram showing dependability of frequencies of interest over time.

3.7 CONCEPTUAL ENERGY HARVESTERS

3.7.1 THE CONCEPTUAL WIND ENERGY HARVESTER

The methodology produced many design parameters, requirements, and constraints. In addition, these areas resulted in avenues for potential innovation and were focused on during concept generation. The following challenges were addressed:

- System may not hang below structure
- Energy is concentrated very close to the bottom of the structure
- Turbulent flow
- Low wind speeds
- Flange and cross frame offer viable attachment points.
- Wind speed is going to be lower at the structure
- Potential for large variation in wind distribution

A combination of concept generation techniques were used to develop solutions to these challenges. The following are iterations on different concept generation results as the design was developed.

The low wind speeds challenge was the first major problem addressed during concept generation. Increasing the rotor speed into the generator was the focus; Figure 14 shows a preliminary sketch. The sketch shows a counter-rotating concept where the rotor spins one direction while the housing that contains the stator rotates in the opposite direction. A counter-rotating concept would double the speed the generator sees with the same input wind.

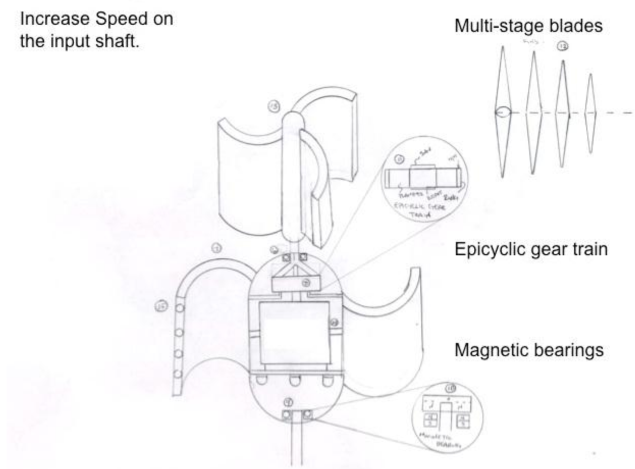

Figure 14. Counter-rotating concept.

The next concept drawing, seen in Figure 15, shows an alternative concept, which has been refined to include other functions. In this concept the speed challenge was addressed by increasing the velocity of the flow (wind). A ring, with an airfoil profile, increases the wind speed by concentrating it into the turbine fins. An epicyclic gear train is used to further increase the speed as it enters the generator. Attaching to the structure was also addressed, and in this concept a strong magnet was identified as a solution for mounting, and simple adjustment of the height of the wind harvester.

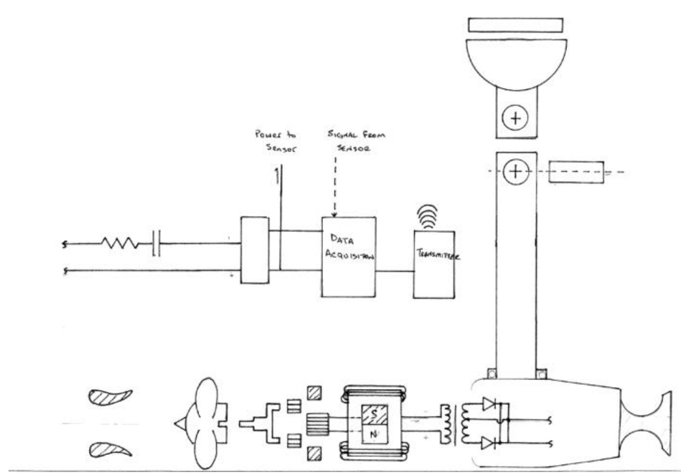

Figure 15. Flow accelerating concept.

The previous concepts create power production at low wind speeds by increasing the speed; however there are many complexities in accomplishing this approach. Other concepts addressed the problem alternatively. Figure 16 shows the power curve of a typical wind turbine, where electricity is not produced at low wind speeds (in this case below 8 mph) [31]. Many factors contribute to this, such as design parameters of the turbine fins, and constraints of the generator. Ideas were generated on how to increase the power output in this region, leading to some interesting ideas.

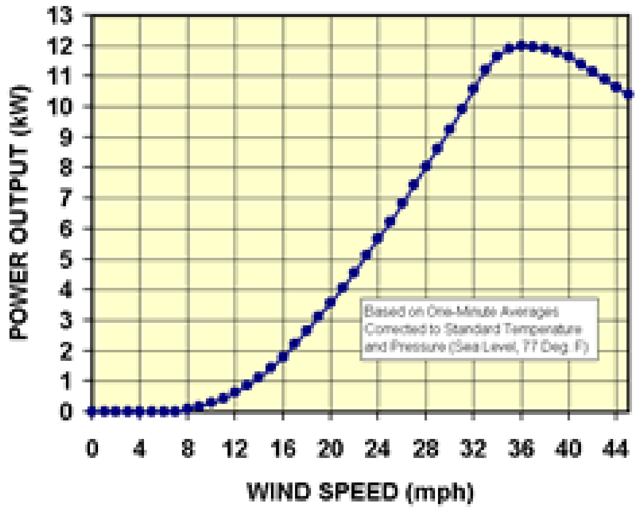

Figure 16. Power curve for small wind generator [31].

A concept to continue to create electricity at low wind speeds was to use a different kind of transducer. Piezo-electric materials create an electric current when deformed or stressed [32]. The concept developed was a hybrid design involving a piezo-electric material and a generator. At low wind speeds, the generator is disengaged, and an arm stresses a piezo-electric strip. As the wind increases in velocity, the generator engages, and the arm no longer flicks the strip to protect the material. Figure 17 shows the initial CAD model for the turbine fins, striking arm, and strip clamp. The use of an omni-directional fin design was adopted to better respond to the turbulent flow challenge.

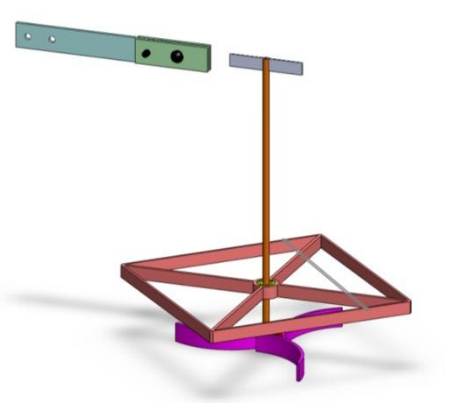

Figure 17. Hybrid wind harvesting striking arm, and strip clamp.

A refined CAD concept is shown in Figure 18, which includes the other functions as well as materials available commercially. The concept made use of the cross frame identified during the field study to mount the wind harvester. Height adjustments were also solved during the clamping to the cross frame of the bridge.

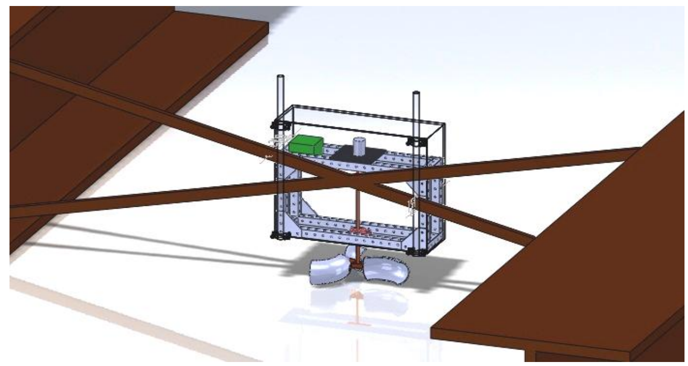

Figure 18. Hybrid wind harvester mounted to cross frame of bridge.

The final concept discussed combines many of the ideas generated to solve the challenges identified in the methodology. The concept can be seen in Figure 18; for low wind speeds, there are several piezo-electric strips. The striking arms can pivot, and will rotate higher as the rotor increases in speed. The ends of the arms are magnets; at low wind speeds they serve as the striking arm, and at faster wind speeds the magnets induce a current in a coil, which is located above the strips. The CAD design seen in Figure 19 has some components missing for clarity, including the coil, the mounting, and additional housing for the electrical components.

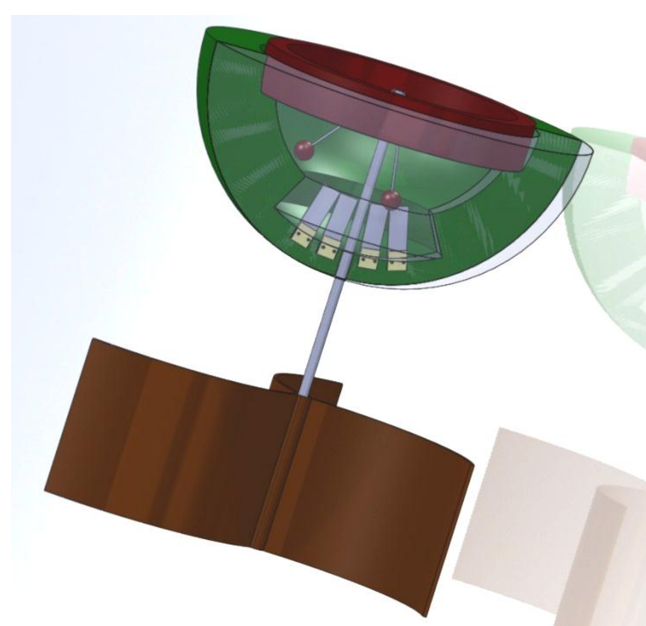

Figure 19. Hybrid wind harvester with magnetic striking arms.

3.7.2 THE CONCEPTUAL ELECTROMAGNETIC VIBRATION ENERGY HARVESTER

A harvester utilizing electromagnetic induction was chosen for development based upon the advantages over piezoelectric and electrostatic harvesters for a bridge monitoring application. The harvester, pictured in Figure 20, includes a magnet assembly which translates vertically guided by an aluminum shaft supported by two linear ball bearings. Magnets which repel the translating magnet are located at each end to serve as the spring. Repelling magnets were used to give a nonlinear compliance, intended to widen the bandwidth as well as provide an easily tunable frequency range as discussed by Mann [39]. The design also allows for these magnets to be replaced by springs for comparison of the harvester's performance as a linear vs. nonlinear system. The repelling magnets are mounted on the end caps which thread onto the main housing. A hole through the center of these magnets allows the shaft to be supported by the bearings, which are mounted inside of the end caps.

The translating magnet assembly is composed of high magnetic permeability and high magnetic saturation Iron-Alloy disks which are sandwiched between opposing Neodymium magnets. The assembly is held together by a nonmagnetic threaded rod with nuts at either end. An aluminum shaft is threaded into each nut to provide a precision, nonmagnetic guide for low friction translation. The iron disks serve to produce a high magnetic flux over a series of coils which surround the translating assembly. This topology was chosen after successful implemented by others in low frequency applications [40, 41].

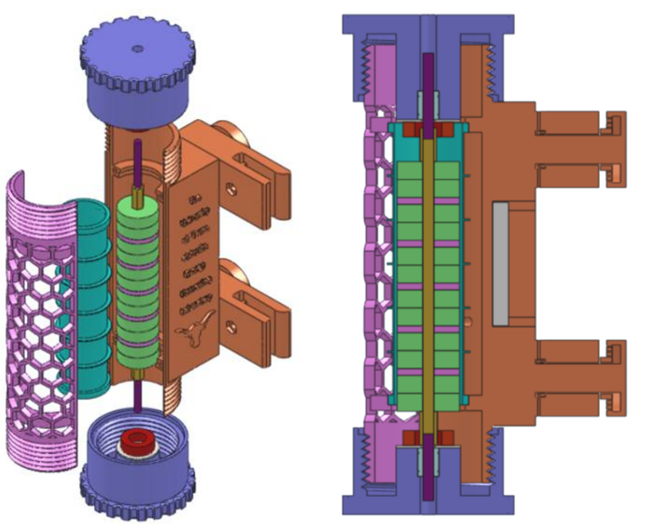

Figure 20. Exploded view (left), and section view (right) of electromagnetic vibration energy harvester concept.

The design is intended for rapid prototyping and thus includes some features which exploit this technology. Most notably is the honeycomb surface which is for visualization of the inner components. 3D printing methods allow the product to be designed for minimum installation and adjustment effort which the user must perform. To tune the resonant frequency, the user would turn both end caps by hand with help from a grip along the cap's edge, and then lock them in place by tightening a pair of set screws. The harvester may be mounted to the bridge by attachment to the cross-frame or web-stiffener plate, as shown in Figure 21. The user would adjust the mounting clamps to the desired orientation then tighten a pair of bolts to secure the harvester to the structure. This process was simplified by including interlocking teeth and a spring within each clamp such that the user may disengage the teeth by pulling the clamp back, rotate the clamp, then release to reengage the teeth. In this manner no tools are required. Figure 22 shows a detailed view of the clip assembly.

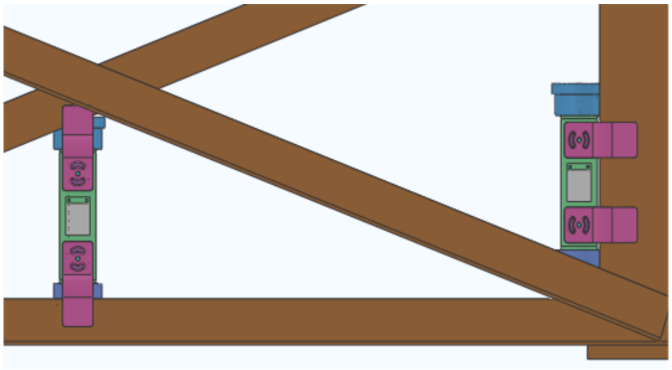

Figure 21. Two possible mounting configurations: to cross-frame (left) and web stiffener (right).

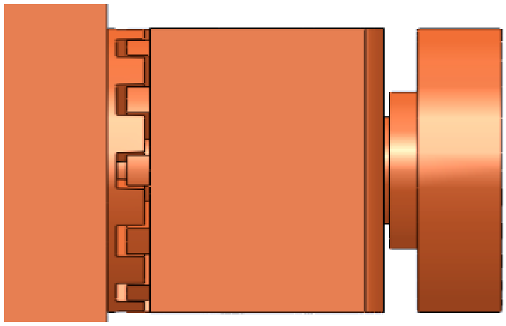

Figure 22. Detail view of mounting clip components: interlocking teeth (left), clip (middle), and spring (right).

3.7.3 THE CONCEPTUAL PIEZOELECTRIC VIBRATION ENERGY HARVESTER

In addition to the electromagnetic harvester, possible vibration solutions involving piezoelectric materials were also assessed. Typical piezoelectric harvesters consist of a cantilever beam and tip mass parameterized to oscillate at resonance. Piezoelectric film on the top and bottom of the beam, referred to as a "bimorph" structure, are subjected to alternating tension and compression, generating a voltage. However, structures capable of resonating at frequencies in the low range necessary for this application experience stress levels that, while well within the yield strength of the flexible metal or plastic beam, far exceed the stress needed to fracture the ceramic piezoelectric material. The concept shown in Figure 23 illustrates a way to work around this limitation by including a mechanical transformation from low frequency and high displacement to high frequency and low displacement. As the main structure oscillates, the tip strikes a plate located under the beam. This impact generates an impulse loading that excites small piezoelectric bimorphs on the tip, which then resonate freely at their own, higher, natural frequency.

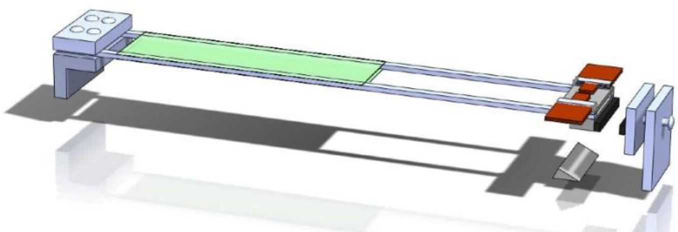

Figure 23. Piezoelectric harvester incorporating a large tuned cantilever capable of exciting smaller independent bimorphs at the tip.

3.8 MAPPING THE ENERGY HARVESTING CONCEPTS TO VIABLE REALIZATIONS

3.8.1 WIND ENERGY HARVESTER

Realizing the wind energy harvester from the different concepts generated demonstrated the methodology's value. The next step was to determine commercially available systems, specifically the generator, the frame, and the piezo-electric material. A manufacturer was found that would form the metal frame to specifications, which involved a two-tiered structure used to house the generator on one tier, and the piezo-electric strip on the other.

For a generator a motor was selected to run in reverse, and so a motor manufacturer was sought. The torque was found using the following equation [33]:

$$M = C_m \rho R^2 H u^2$$

where M is the torque, C_m is a performance coefficient, ρ is the density, R is the blade radial length, H is the blade height, and u is the wind speed. The manufacturer provided the power given an input torque using the following equations [42]:

$$P_{mech} = \frac{\pi}{30000} Mn$$

where M is the input torque on the rotor shaft, and n is calculated by:

$$n = \frac{u}{R}\eta$$

where η is the drive train gear ratio. The selected motor would output approximately 400 mW at wind speeds of 3 mph, a conservative estimate to ensure production of the required 200 mW.

For the low wind speed transducer, a piezo-electric strip that produces the highest output under stress was sought. Lead zirconate titanate (PZT) was selected and acquired with the electrical leads, and mounting attachment already included [34]. The striking arm was then developed to stress the material with minimal loses.

The supporting structures, like the turbine fins, rotor shaft, and coupling components, were all fabricated. The resulting wind energy harvester can be seen in Figure 24. The load for the harvester has not yet been completed; a substitute load was used for the testing, and National Instruments LabVIEW was used to acquire the data. Additional testing is currently underway; the initial testing generated power in the expected range identified during Step 1.

3.8.2 ELECTROMAGNETIC VIBRATION ENERGY HARVESTER

The harvester was built using MATLAB and Simulink with the SimScape add-on to size components and simulate the performance. The measured bridge acceleration data was used to estimate power output and maximum displacement under realistic operating conditions. The nonlinear stiffness of the repelling magnets was measured over a range of separation distances and used in the simulation as well as to calculate the tunable range as was shown in Figure 11. The concept shown previously in Figures 20-22 was built additively (3D printed) using selective laser sintered Nylon plastic. This manufacturing capability allowed for a minimum number of parts and minimal assembly. In fact, the mounting clamps, teeth and springs which move relative to each other were printed as one single part. The components which could not be manufactured this way were purchased or machined then assembled. The finished prototype is shown in Figure 25 with two mounting clamp orientations. Initial testing on a shaker table has shown a peak power of 26 mW at 2.2 Hz and acceleration amplitude of 0.08 g.

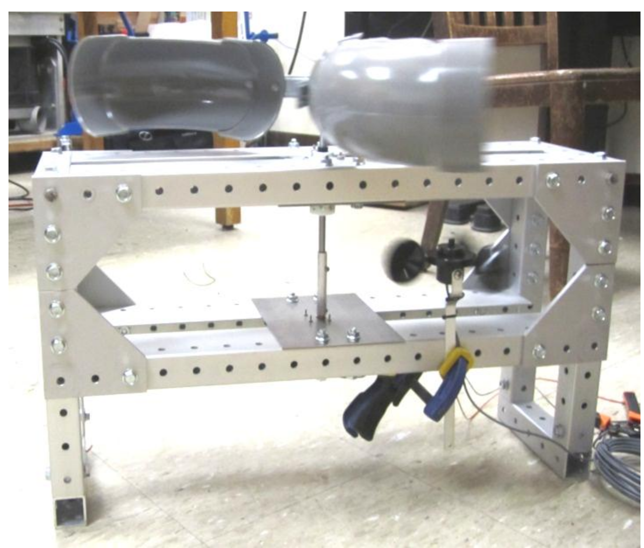

Figure 24. Wind energy harvester proof of concept.

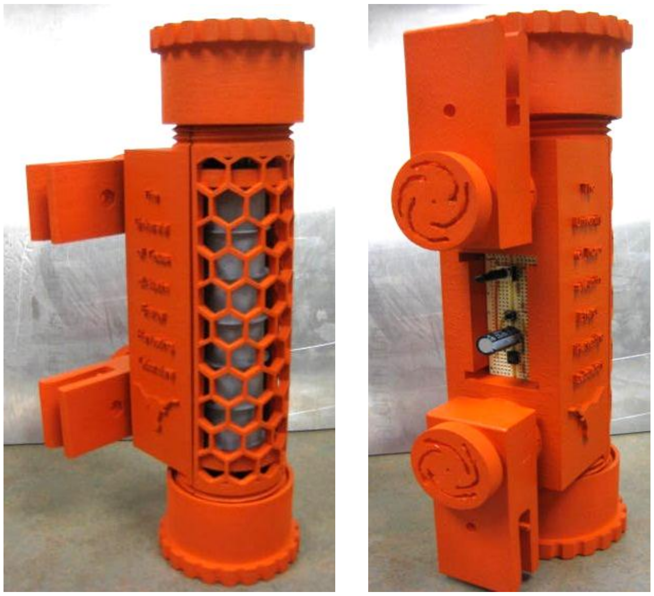

Figure 25. Prototype (left) and translating magnet structure (right).

3.8.3 PIEZOELECTRIC VIBRATION ENERGY HARVESTER

The main harvester structure consists of two beams of aluminum and a large tip mass of steel. The beam dimensions and tip mass were sized to maximize the mass (and thus the possible power output) while maintaining a natural frequency of 2 Hz and a factor of safety of 5 under static loading. Two MIDE Volture vibration harvesters were attached to the tip. For ease of installation and testing, these bimorphs were attached with magnets; however, predrilled holes are available for permanent installation. Following construction, the harvester was tested through several experimental procedures. First, the natural frequency of the harvester was determined. Because a shaker table was not yet operational, an initial test displaced the tip and allowed free vibration. This revealed a natural frequency of 2.2 Hz without the bimorphs installed on the tip. With the harvesters installed, subsequent testing on a shaker table revealed resonance at a frequency of 2.07 Hz. Under forced vibration at 2 Hz, the main beam oscillated at resonance, but the tip bimorphs did not excite and contribute a significant amount of voltage. The original concept called for opposing magnets (one on the moving tip, one fixed) to introduce a non-linearity that would excite the bimorphs. This hypothesis, however, was not supported by the laboratory tests. An alternate means for exciting the bimorphs, illustrated in the CAD model earlier (Figure 23), uses an impact each oscillation to successfully excite the bimorphs. Figure 27 shows power output from a single bimorph under a sinusoid input at 2 Hz under different resistive loads and striker positions.

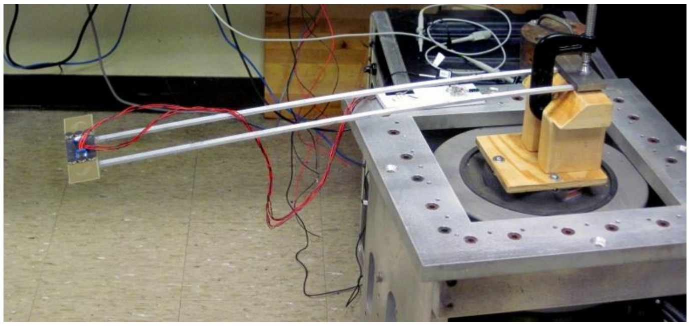

Figure 26. Piezoelectric harvester installed in test fixture on a shaker table.

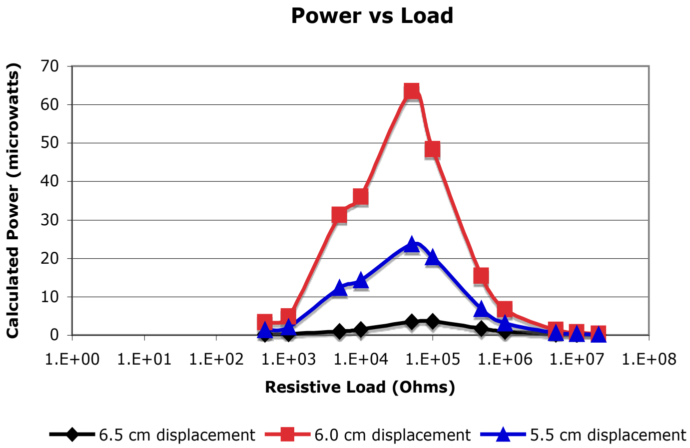

Figure 27. Power output from one bimorph using striker plate.

4.0 GENERAL DISCUSSION AND CONCLUSIONS

This paper presents a methodology for developing energy harvesting technology to be used with a wireless sensor health monitoring system. The methodology, outlined in Section 2 and demonstrated in Section 3, produced three proof of concepts in two domains. Unique aspects of the application led to the use of different harvesters, which provide a range of assets and limitations. The examples demonstrate the methodology's ability to produce innovative solutions to the challenges inherent in this application.

Low power energy harvesting is a challenging problem, and insights about the methodology, design choices, and concepts were gained during the progression through the methodology; these insights can be grouped into four main categories: holistic, inventive, technological, and technical.

While following the methodology it became apparent that Step 2 is fundamental for gathering holistic insights into the energy harvesting system. Many design decisions are identified during this step, and attention to detail is important. A well thought out Step 2 will provide valuable information that will determine the success of the developed energy harvester as a system.

Many inventive insights occurred when mapping concepts to viable realizations. A plethora of opportunities were discovered in this stage to fill gaps in the available technology.

This step also showed the importance of Step 7, how it is essential to be expansive when generating concepts, generating multiple solutions to address each problem.

The technological shortcomings discovered at different steps of the methodology give insights into opportunities for innovation within energy harvesting. For example, during Step 2, it was documented that the structure's natural frequency was dependent on temperature, and changed throughout the day. This was also noted during Step 3 because the temperature fluctuates from one season to the next. The vibration harvesters were greatly affected by natural frequency, and so developed innovative ways to tune the harvester. A hybrid wind harvester, utilizing multiple transducer technologies, was pursued because energy conversion at very low wind speeds was missing in commercial products.

Technical insights, such as addressing the 10-year life and no maintenance requirements greatly influenced Step 5 (directly related to storage capabilities) and minimizing failure modes. Inventive concepts directly lead from discussions of this technical insight including the concept seen in Figure 18, which attempts to combine the hybrid system's striking mechanism, generating coil, and safety break into as few parts as possible. In addition, many of the concepts generated offered extreme technical problems; the decision was made to pursue the "low-hanging fruit". However, as the technology progresses, the technically challenging concepts provide the opportunity to develop inventive technology and innovative harvesters.

Energy harvesting is becoming an important alternative to fossil fuels on a large scale. The applications where energy harvesting is not only feasible, but is a significant option are expanding. Energy harvesting may also give systems expanded abilities that are currently limited by power sources. Previously, battery life and wires prevented autonomous systems in remote locations, but innovative energy harvesting designs can bring these systems an alternative power source.

Although the application was specific to bridges, the methodology can be applied to many other harvesting situations, and provide valuable insights to the field of energy harvesting. Once a harvesting subsystem is determined to be capable of providing the required power, other aspects such as cost, maintenance, and reliability will determine implementation. Continued work in this field will offer new solutions and expand the capabilities of health monitoring in the future.

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