Ultrasonic Underwater Transmission of Composite Turbine Blade Structural Health

A. Heckman,[1] J. L. Rovey,[1*] K. Chandrashekhara,[1] S. E. Watkins,[1] R. Mishra,[2] and D. Stutts[1]
[1]Missouri University of Science and Technology, Rolla, Missouri, 65409, USA
[2]University of North Texas, Denton, Texas, 76203, USA

ABSTRACT

A health monitoring approach is investigated for hydrokinetic turbine blade applications. In-service monitoring is critical due to the difficult environment for blade inspection and the cost of inspection downtime. Composite blade designs provide a medium for embedding sensors into the blades for in-situ health monitoring. The major challenge with in-situ health monitoring is transmission of sensor signals from the remote rotating reference frame of the blade to the system monitoring station. In the presented work, a novel system for relaying in-situ blade health measurements is described and demonstrated. An ultrasonic communication system is used to transmit health data underwater from the rotating frame of the blade to a fixed relay station. Data are then broadcast via radio waves to a remote monitoring station. Results indicate that the assembled system can transmit simulated sensor data with an accuracy of ±5% at a max sampling rate of 500 samples/sec. A power investigation of the transmitter within the blade shows that continuous max-sampling operation is only possible for short durations (~days), and is limited due to the capacity of the battery power source. For a 1000 mA-hr battery to last two years, the transmitter must be operated with a duty cycle of 368, which means data are acquired and transmitted every 59 seconds. Finally, because the data transmission system is flexible, being able to operate at high sample rate for short durations and lower sample rate/high duty cycle for long durations, it is well-suited for short-term prototype and environmental testing, as well as long-term commercially-deployed hydrokinetic machines.

1. INTRODUCTION

The energy in flowing river streams, tidal currents, and waves is being investigated as a potential source of renewable energy.[1-2] Because hydrokinetic systems must be located underwater where access is difficult, monitoring technologies are important for timely notification of operation and maintenance (O&M) issues. In the following sections we describe a data transmission system that can transmit structural health information about the turbine blades of a hydrokinetic energy system.

Hydrokinetic energy systems are designed to convert kinetic energy of a fluid (e.g., river or tidal current, waves) into electricity. They are generally classified in two broad categories: (a) wave energy conversion devices and (b) rotating devices. Wave energy conversion devices create a system of reacting forces in which two or more bodies move relative to each other while at least one body interacts with the waves. Rotating devices are deployed within a stream or current capturing kinetic energy from flowing water via a turbine that powers a generator. In a typical rotating device, the river or tidal current passes through a protection screen and into the turbine channel. Kinetic energy of the fluid causes the turbine to rotate and this rotational energy is extracted by the generator attached at the top of the turbine. Power from the hydrokinetic turbine is then coupled to the electrical grid through a power converter. A number of resource quantization and demonstrations have been conducted throughout the world and it is believed that both in-land water resources and the offshore ocean energy sector will benefit from this technology.[3-4] A 2009 market analysis by Pike Research predicts the marine and hydrokinetic energy market value to grow considerably over the next 5 years. Specifically, at the end of 2008, the total installed capacity of marine and hydrokinetic systems was only 10 MW. By 2015, market predictions based on planned projects and installations suggest that between 2.7 to 10 GW of installed power will be available, representing a market value between $6 to $20 billion.[5] With this much potential gain, there is much interest in the continued development of hydrokinetic energy systems.

[*] Author E-mail Addresses: roveyj@mst.edu, chandra@mst.edu, and steve.e.watkins@ieee.org
Contact Author: J. Rovey, 292D Toomey Hall, Missouri University of Science and Technology (formerly University of Missouri-Rolla), 400 W 13th St., Rolla 65409-0040, 573-341-4613

Hydrokinetic energy systems must be remotely monitored. By their very nature the hydrokinetic system is remotely located underwater in areas that are generally difficult to view, inspect, and analyze. What's more, many hydrokinetic energy systems plan to be located off-shore or in remote areas far from dense population. For example, a study of potential Alaska river in-stream power plants selected three river locations where the nearest villages have populations of 50-100 people and the nearest cities are 100's of miles away.[6] Simply getting to these sites represents a significant challenge. Accessing the components to perform any kind of analysis would be a difficult, expensive, and nearly impossible task.

The main benefit of remote monitoring is lower O&M costs and a higher return on investment. The Pew Center on Global Climate Change recently found that "O&M costs could remain high due to difficult access and working conditions unless machines are developed that can be unattended for long periods of time."[7] In other words, leaving hydrokinetic systems unattended and remotely monitoring them is imperative for reducing O&M costs and making it a viable and promising technology. It is difficult to estimate the future O&M costs of hydrokinetic systems because the technology is still being developed. However, wind energy systems are plagued by similar issues and, over the lifetime of the machine, have typical O&M costs of 70-95% of the total investment cost.[8] These estimates were for a project that considered 600, 750 kW wind turbines. O&M costs are typically higher for smaller power machines and near-term hydrokinetic systems are likely to be a few 100 kW, in which case O&M costs may be higher. In other words, reducing O&M costs with remote monitoring may be the only salvation for making these systems viable on a large scale with widespread use.

The structural health of hydrokinetic energy systems needs to be monitored. While methods for monitoring voltage and power output have been developed, the turbine blade is the critical structural component for energy extraction and it also bears the most dynamic load. Fatigue causes degradation of structures and eventually leads to structure failure. Over time, small cracks develop and propagate, reducing the structure integrity, and eventually cause it to break and fail. In addition to the natural slow fatigue of the blade structure, there is also significant concern about transient impacts and loads due to environmental factors. Oceans and rivers are heterogeneous bodies of water that contain aquatic and marine organisms, vegetation due to run-off, and pollution that pose a significant hazard to hydrokinetic energy systems. Multiple reports have been published evaluating the effect of hydrokinetic energy systems on marine life (e.g., fish and other aquatic organisms, diving birds, and mammals).[9-12] While a single impact may not be immediately catastrophic, it can create a crack at the point of impact that eventually propagates, compromising the structural integrity of the blade and leading to failure. In addition, other transient environmental effects may cause increased loads on the blade, degrading structural integrity. For example, earthquakes, tsunamis, and flooding are all natural phenomena that will occur and may cause damage.

There are multiple scenarios where remote monitoring of turbine blade structural health is beneficial. For example, it can lead to timely replacement of a blade by notifying service personnel when the blade structural integrity is likely to soon fail; in the event of damage due to transient environmental effects, the remote monitor would immediately notify service personnel so the system could be repaired (patched) quickly to minimize down-time; knowledge of the turbine blade structural health could lead to enhanced operational lifetime. For example, as the blades age, the system may be operated at reduced capacity to reduce structural load, thereby maintaining power generation (albeit at a reduced level) for a longer period of time.

Application of remote monitoring technology to hydrokinetic energy systems is still in its infancy. Technologies exist to remotely monitor some of the hydrokinetic system operational parameters, such as voltage, frequency, and power output. However, the ability to monitor the health of the structure, specifically, the turbine blade, has yet to be developed. There are many techniques for monitoring the health of any structural component. However, most of these techniques are off-line monitoring technologies, which mean they cannot be used on a system while it is operating. For example, acoustic emissions, thermal imaging, ultrasonic detection, fiber optics, laser Doppler vibrometry, electrical resistance-based damage detection, strain memory alloy methods, x-radioscopy methods, and eddy current methods have all been used to assess the structural integrity of a wind turbine blade.[13] However, of these methods, only acoustic monitoring has been used while the blade was in service.[13-15]

The challenge with in-service monitoring the structural health of any turbine blade is that it is a rotating component that is always moving when the system is operating. So connecting a wire to a fiber optic, acoustic sensor, electrical strain gage, etc. is not practical. In other words, structural health data need to be acquired and then wirelessly transmitted from the rotating frame of the blade. This was the approach that successfully showed radio transmission acoustic monitoring of a wind turbine blade.[13-15] Simply adapting this wind turbine system to a hydrokinetic turbine blade is not possible because in an aquatic environment radio communication is only possible for short distances (< 1 m), at very low frequencies (30-300 Hz), with large antennae, and high transmission power.[16]

Structural health monitoring of hydrokinetic turbine blades has never been investigated and is the focus of the work presented here. In the following sections we describe a proof-of-principle experiment that demonstrates transmission of a simulated structural health monitoring signal through the aquatic environment and then wirelessly through air to a remote monitoring station. A schematic of the general concept is shown in Figure 1. Composite turbine blades, embedded with a fiber optic strain gage and acoustic transducer, are attached to the turbine and used to generate electricity. The fiber optic strain gage senses the degradation of the blade structure over time due to cyclic loading (fatigue) and transient environmental factors. A power and electronics module inside the blade conditions the fiber optic strain gage signal into an acoustic signal that is transmitted by the acoustic transducer. The acoustic waves propagate through the water to a receiver that is located near the shore or on the system foundation. The received acoustic signal is then broadcast above water long distances by radio waves to the monitoring station. The broadcast signal is then interpreted at the monitoring station, yielding strain data from the blade, which can be used to notify service and maintenance personnel.

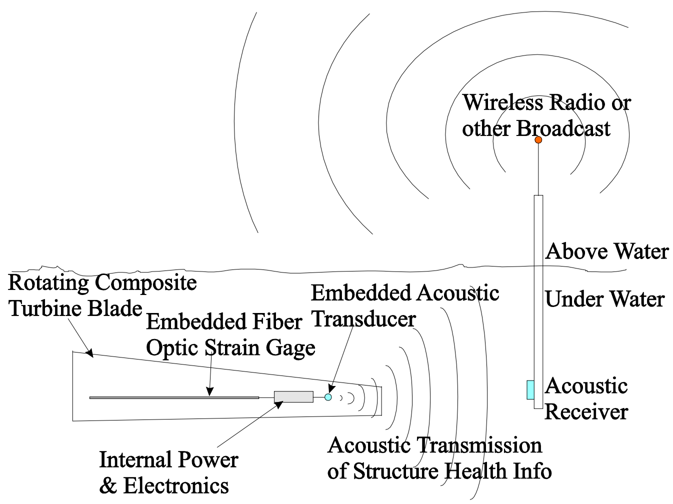

Figure 1. Schematic of the hydrokinetic turbine blade structural health monitoring concept.

In the following sections we describe a proof-of-concept demonstration of the data transmission part of the blade structural health monitoring concept. We have already demonstrated a composite turbine blade with embedded fiber optic strain gage in Ref. 17. In the following study, a simulated strain gage output was used as the input to the data transmission system. In addition to demonstrating the feasibility of the technique, we also present results from a power analysis that is used to assess the viability of the approach and its suitability for both commercial and prototype hydrokinetic energy systems. Specifically, we envision this concept and the resulting capability can enable blade structural health monitoring in both long-term commercial hydrokinetic system deployment, as well as prototype environmental impact studies.

2. Data Transmission Process and System

Remote monitoring of the structural health of a hydrokinetic turbine blade requires transfer of data from the measurement location to the monitoring station. For the concept investigated here, structural health data are acquired using internal turbine blade diagnostics (fiber optic strain gages) and this information is acquired within the rotating reference frame of the blade. Data must be transferred from the blade to the remote monitoring station. A schematic of the data transfer process is shown in Figure 2. The structural health data (strain gage output) are transmitted underwater from the rotating frame of the turbine blade to a nearby stationary underwater receiver. The data can then be broadcast wirelessly using one of many conventional techniques (RF, Bluetooth, microwaves, etc.) to notify the remote monitoring station.

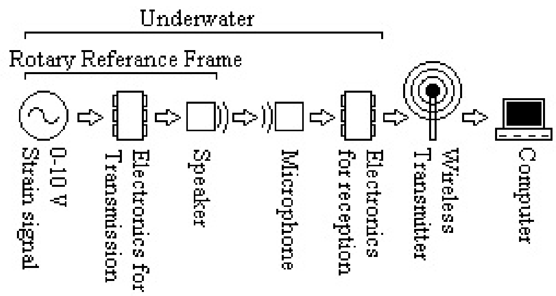

Figure. 2. Schematic diagram of main components of the underwater acoustic communication system.

The system described here uses an acoustic communication system for underwater data transmission, while the above water (air) data transmission uses a wireless Bluetooth transmitter. As shown in Figure 2, a 0-10 V source simulates the data output from a strain gage embedded in the turbine blade.[17] This data signal is encoded by the transmitter electronics and acoustically transmitted through the water. The encoded data signal is received by an underwater microphone connected to the receiver electronics, which then decode the signal and broadcast it wirelessly through air via Bluetooth. A remote laptop with a Bluetooth receiver serves as the remote monitoring station.

The following sections describe the details of the data transmission system. First the transmitter and receiver circuitry are described. Then the rationale for selecting 40 kHz as the underwater acoustic transmission frequency is explained. Next the prototype software used to operate both the transmitter and receiver electronics, and encode and decode the data, is described. Finally, the bench top setup for testing is described.

2.1 Acoustic Transmitter and Receiver Circuitry

The acoustic transmitter and receiver circuits consist of two main components: a microcontroller and an ultrasonic transducer. The foundation of the transmission and reception circuitry is two PIC18F46K20 Microchip microcontrollers (MCUs), one for each circuit. These MCUs provide the necessary processing to encode and decode the data. They were selected because they have a variety of useful built-in features, such as several analog to digital conversion (ADC) ports, the capability of implementing EUSART serial communication, and an extremely low power consumption when ‘sleeping’. A pair of MA40MF14-5B Murata ultrasonic transducers serve as the acoustic transmitter and receiver. These transducers are optimized for 40 kHz frequency, and this data transmission frequency was selected based on the rationale described below. Details regarding both the transmission and reception circuits are described next.

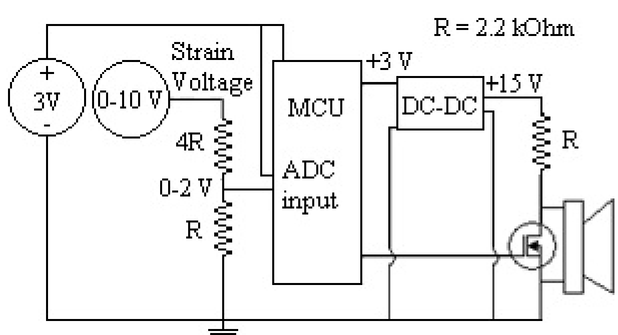

Figure 3. Transmitter Circuit

The main tasks of the transmitter circuit are to measure the strain sensor voltage, measure the battery voltage, enter and awake from “sleep” mode, encode the strain data into an acoustic signal, and transmit the data with the ultrasonic transducer. A schematic of the transmitter circuit is shown in Figure 3. Measuring the sensor voltage and battery voltage is done using the MCUs built-in ADC feature. Measuring the battery voltage allows us to also track the life of the power supply. The voltage divider at the strain sensor is used to lower the 0 to 10 V simulated strain gage signal to 0 to 2 V, since the MCU input pins can only take 0 to 5 V. The effect of duty cycle on the potential lifetime of the monitoring system is studied in subsequent sections by using the “sleep” feature of the MCU, which is controlled using the MCU software. MCU software is also used to encode the measured strain gage voltage into the acoustic transmission signal. Finally, transmission of the acoustic signal uses the 40 kHz ultrasonic transducer, a DC to DC converter, and a logic level mosfet. While initial tests showed that the MCU alone can drive the transducer, the resulting ultrasonic signal was too weak to ensure accurate reception. Instead a simple amplification circuit is used. The MCU output operates the mosfet switch, which in turn modulates the transducer driving signal from the DC to DC converter. Finally, a 3 V power supply is used to power the circuit.

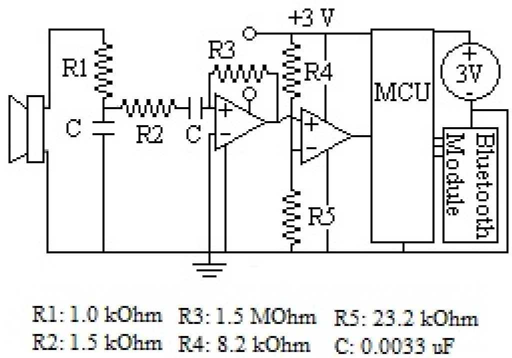

Figure 4. Receiver Circuit

The major tasks for the receiver circuit are to receive the acoustic signal, process it, and re-transmit wirelessly through air (Bluetooth in this case). An ultrasonic transducer receives the transmitted acoustic signal. This signal is passed through two filtering circuits to remove background noise, a passive low pass filter and then an active high pass filter. The low pass filter has a cut off frequency of approximately 48 kHz, while the active high pass filter has a cutoff frequency of approximately 32 kHz and a gain value of 1000. The filtering process allows the required 40 kHz signal through while removing anticipated background noise that would be found in a river, such as rain, wind, and fish acoustics. It also removes acoustic signals above 40 kHz that would likely be due to man-made sources, such as boat motors, range finders, and other sonar products. After being filtered and amplified, the signal is then modified by a comparator. The comparator converts the roughly sinusoidal signal into a square wave pulse train, which is much easier for the MCU to process.

2.2 Acoustic Transmission Frequency

A 40 kHz acoustic transmission frequency was selected based on three main considerations. First, ambient noise sources encountered in the hydrokinetic energy system environment, both natural and artificial, were considered. Second, we considered the audibility of the signal to humans. Finally, the relationship between attenuation rate and data transmission rate at acoustic frequencies was considered.

Two natural sources and two artificial sources of ambient noise are likely to be encountered underwater in a river. The two natural sources are wind and rain noise, while the artificial noise sources originate from boat motors and ultrasonic range/fish finders. Both wind and rain have distinct acoustic power spectrums.[18] Wind noise can be approximated using Knudsen curves, which show that at about 500 to 1000 Hz, the magnitude of wind noise decreases with increasing frequency. While the wind noise does not disappear entirely in the ultrasonic region, it is severely reduced in strength and is not considered a significant noise source. Rain has a distinct peak in strength at around 14 to 16 kHz,[18] and then also decreases in strength with increasing frequency. However, rain has been shown to suppress wind noise, and its peak is closer to the ultrasonic range. As such, of the two natural sound sources rain is the more concerning. For artificial noise sources, motor boat noise does not exceed 1 kHz,[19] and therefore is not a concern for the ultrasonic frequencies used here. However, the commercial sonar products that many boats are equipped with are a concern, as they rely on producing ultrasonic pings to visualize the underwater environment. The frequency for commercial sonar applications ranges from 20 kHz to 400 kHz generally, and the most common frequencies used are 50 kHz and 200 kHz. Therefore selecting an ultrasonic communication frequency away from 50 or 200 kHz is best for mitigating interference from such ultrasonic devices.

The second criterion we evaluated was the audibility of the communication signal to humans. Specifically, we require the operating frequency to be inaudible to the human ear. This criterion is selected to reduce noise pollution that would potentially be generated by the system operation, and as such it is highly desirable that the signal produced be inaudible to both humans and many aquatic river organisms. The selection of an ultrasonic frequency is an easy way to alleviate this concern, as humans cannot hear in the ultrasonic range and many fish species can only hear in a range of 20 to 300 Hz.[19]

The third criterion considered was signal attenuation and transmission rate in an underwater environment. In acoustic communication in water, the rate of attenuation and maximum data transmission rate are directly linked. More specifically, as frequency increases both the attenuation rate and the data transmission rate increase. Thus, a very low frequency signal can travel very large distances in water, but has a very slow rate of data transmission, whereas a high frequency signal travels shorter distances, but has higher data transmission rate. The attenuation of acoustic waves in seawater is shown in Figure 5 and is given by Eqn. 1,[20] where f is the frequency in kHz, T is temperature in degrees Celsius, and D is depth underwater in kilometers. Figure 5 assumes a temperature of 22 ºC and depth of 1 m.

$$\alpha = 0.00049 f^2 \exp(-(T/27 + D/17)) \tag{1}$$

The transmission rate is simply the frequency of the waveform divided by the number of periods that are used to represent one bit of data. The system described here uses 5 periods of the 40 kHz waveform to represent one bit, as described in the next section, and the resulting transmission rate is also shown in Figure 5. Since having both low attenuation rate and a high data transmission rate are mutually exclusive, the operating frequency for the system must be selected for the systems' requirements.

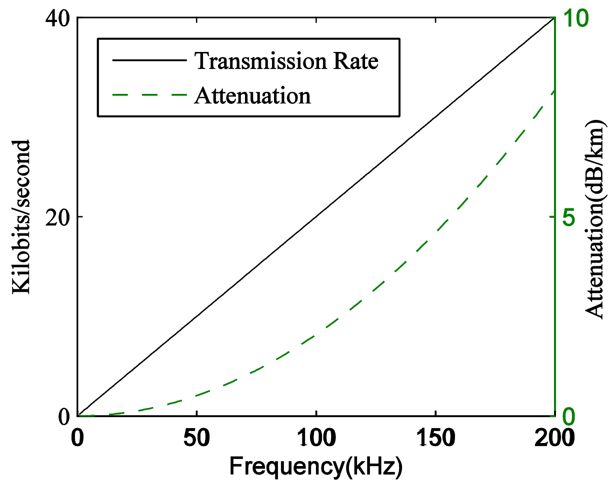

Figure 5. Attenuation and transmission rate vs frequency

Based on these factors, we selected a 40 kHz signal. This ultrasonic frequency is not near either 50 or 200 kHz, and therefore alleviates both natural and artificial noise concerns. Because 40 kHz is in the ultrasonic frequency range it is also inaudible to humans and most aquatic animals. Finally, 40 kHz has low attenuation rate on the order of 0.5 dB/km and relatively high 8 kbits/sec rate of data transfer. While higher frequency and the resulting higher data transfer rate would increase the "real-time" nature of the transmission, for this proof-of-concept system we place more emphasis on low attenuation so as to maintain a high signal-to-noise ratio and maintain reliable communication.

2.3 Data Encoding

The software running on the two MCUs encodes the structural health data for underwater transmission from the rotating blade and then decodes the data once received at the static relay station. In order to transmit the acquired data (simulated here as a voltage signal between 0-10 V), the transmitter MCU encodes the data before it is sent. This encoding for transmission is a modified on-off keying (OOK) encoding scheme, where a '1' data bit is indicated with 5 periods of the 40 kHz sine wave and a '0' data bit is indicated with a period of silence that lasts the equivalent time of 5 periods of the 40 kHz sine wave (i.e., 125 µs). Figure 6 illustrates the encoding scheme. We have modified the standard OOK encoding by including four clock train '1' bits at the beginning of the data transmission sequence and also padding the space between each clock-train bit in the transmission with a period of silence. This modification reduces the effect of echo encountered in the underwater environment. An example of a transmitted '1' data bit and the subsequent echo is shown in Figure 7. The four clock bits allow the receiving circuit to synchronize with the transmitting circuit, thus preventing the receiving circuit from triggering on an erroneous echo signal. In effect the initial clock train of data provides an initial condition from which the receiving circuit can synchronize the remainder of the transmitted data bits. In this way the transmission and reception circuits are synchronized and the 10-bit structural health data are transmitted from the rotating blade to the static relay station.

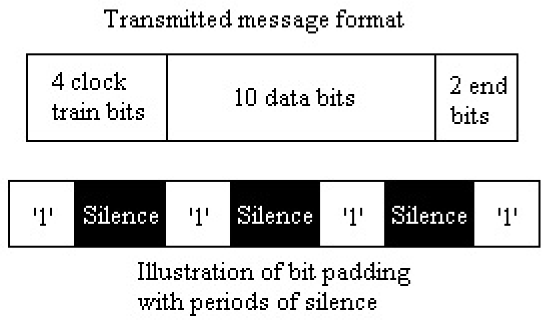

Figure 6. Signal encoding scheme.

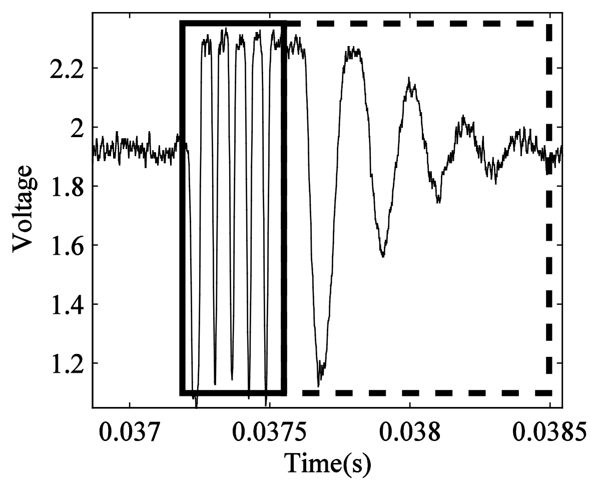

Figure 7. Transmitted ‘1’ bit (solid box) and the following echo (dashed box)

The MCU of the receiver circuit listens for and receives transmissions, determines if the transmission is valid, decodes the transmission, and then rebroadcasts the data via Bluetooth. Since the receiving circuit is not in the rotary frame of reference, it can be powered directly from the turbine (or wall during lab testing) and therefore does not spend time sleeping like the transmitter. Instead it spends most of its time listening for an incoming transmission. Upon initial detection of a 40 kHz signal, the MCU determines if the signal is the 4-bit clock-train indicating initiation of data transmission by listening for the four ‘1’ bits with silence in between (as illustrated in Figure 6). The MCU then times the duration between each of the clock bits, and takes the average time of the periods of silence between them. In this way the MCU synchronizes with the transmitter. The next 10 data bits are then received as well as the two stop bits, which serve to indicate that the message has been successfully transmitted. If both stop bits are not received, the MCU rejects the data as not being a valid communication. In the case of correct transmission, the 10 data bits are converted back to a positive integer value and retransmitted via the Bluetooth. Following Bluetooth transmission, the receiver MCU returns to listening for the next communication.

2.4 Static Bench Top Testing

The electronics and software were tested to validate correct operation and to characterize the power consumption of the system. For these experiments a static bench top setup was used. For this setup only the acoustic transducers were placed in water, the other electronics are dry, and all components are statically mounted, i.e., there is no rotating turbine blade reference frame, only the lab frame. A photograph of the setup is shown in Figure 8. In the figure, a (1) NI USB-6008 DAQ provides a constant 3 V power supply to the circuits. A (2)

Sparkfun BlueSMiRF Silver chip is the Bluetooth transmitter connected to the (3) receiver circuit. Both the (3) receiver and (4) transmitter circuits are each connected to an ultrasonic transducer in the (5) aquatic environment. Finally, a (6) Tektronix TDS-2014B oscilloscope was used to measure voltage input and output from the various electric circuit components. To characterize the power of the transmitter circuit, the required current and time duration of the different modes of the MCU were measured. The current was measured with a Fluke multi-meter in series with the battery and circuit, while the time duration for each mode was measured with the oscilloscope. Finally, isolated operation of the transmitter circuit, by replacing the DAQ power supply with a 3 V coin cell battery, showed identical results for all tests.

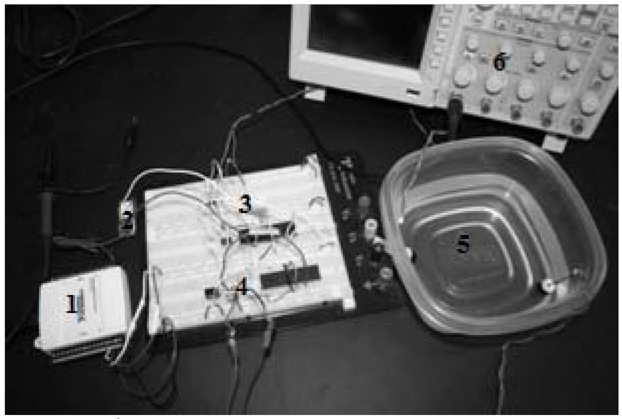

Figure 8. Bench top setup for communication validation and power consumption investigation.

3. Results and Discussion

The structural health data transmission process described above was tested in a static environment. First we describe the initial validation process that demonstrates accurate transmission of simulated structural health data from the blade to the remote monitoring station. This process is demonstrated for multiple simulated health data signals. Then we analyze the power requirements of the system and investigate the effect of operation mode on transmitter power supply lifetime.

3.1 Data Transmission Validation

To demonstrate and validate the data communication process, several different health data waveforms were communicated. These different waveforms simulate possible outputs from the embedded fiber optic strain gauge. Initially the error associated with the ADC of the MCU is quantified, along with the precision of the measurement electronics. Then data from the transmitted waveforms is presented, which include a constant value, a square wave, and one half-cycle of a sine wave. For the results presented below, the communication system is tested in a static benchtop environment.

The ADC of the MCU has a resolution of 10 bits. This corresponds to 1023 separate voltage values that can be measured in the range from 0 V to the saturation voltage of the ADC, which is either 5 V or the voltage supplied to the MCU. In this case, the MCU supply voltage is 3 V, meaning that the theoretical precision of the ADC is 2.9 mV. To experimentally determine the accuracy of the ADC and associated transmission circuitry, we applied known voltages to the voltage divider and measured the resulting received signal from the monitoring station. Specifically, voltages from 3.0 to 1.2 V were applied with a resulting error of ±5%. So the 10-bit resolution provides a precision of 2.9 mV with an error in the reported data of ±5%.

Received data for the constant value and square wave waveforms are shown in Figure 9. For the constant value data transmission, a voltage of 0.499±0.005 V was input into the transmitter circuit. As Figure 9 shows, the remote monitoring station received 50 data points over a time period of 6.2 seconds, all of which have a value of 0.499±0.005 V. For the square wave, the period of the wave was chosen as 10 data samples with a min and max voltage of 0.367±0.005 V and 0.733±0.005 V, respectively. The waveform was connected to the transmitter circuit and the remote monitoring station received the signal shown in Figure 9, with all output voltages within ±5% of the input.

Results from the half-cycle of a sine wave data transmission are shown in Figure 10, along with the input signal. A slowly varying 0.08 Hz sine wave with an amplitude of 4.70±0.01 V was the input. Over the 6.2 second long half-cycle, the communication system transmitted 50 data points corresponding to discretized points of the sine wave. The received data are within the previously measured ±5% of the measured input voltage.

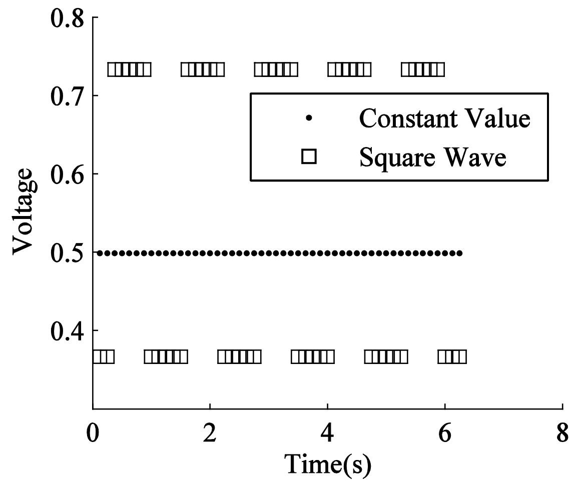

Figure 9. Constant and square wave simulated structural health data transmitted to the remote monitoring station.

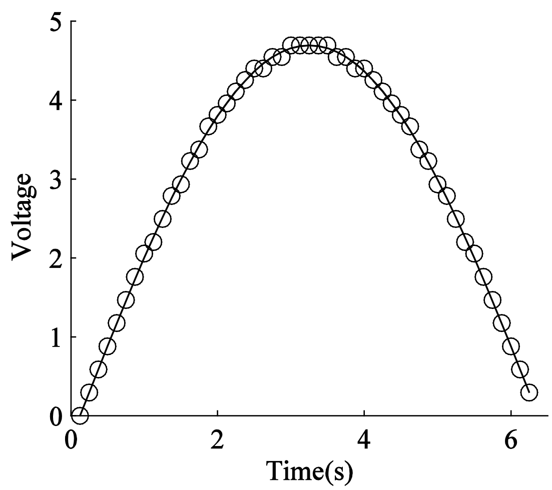

Figure 10. Half-cycle sine wave simulated structural health data transmitted to the remote monitoring station.

3.2 Power Analysis

The power requirements of the transmitter circuit are investigated in order to assess and predict the operational lifetime of the communication system. We envision the transmitter circuit embedded into the hub of the turbine shaft and battery powered within the rotating reference frame of the turbine. While other power options are available, including energy harvesting and a shaft-mounted power take-off, the following analysis assumes the transmitter is operated with a battery of known capacity. The receiver circuit is statically located and can be fed power directly from the generator, so its power consumption is not limited and not investigated here.

Power consumption is calculated using the measured voltage and current output by the power supply of the transmitter circuit. Isolated operation of the transmitter circuit, by replacing the DAQ power supply with a 3 V coin cell battery, showed identical results. Current drawn from the supply was measured for the three possible modes of transmitter circuit operation: sleep, sampling, and transmission. The time the transmitter spends in each of these modes is also measured. These results are given in Table 1. The 'X' used in Table 1 is the duty cycle, the ratio of time spent "asleep" to time "awake". A plot of the current consumption of the transmitter as a function of duty cycle is shown in Figure 11.

Table 1. Transmitter current usage by mode (3 V battery supply)

Mode	Time (ms)	Current (mA)	Current*Time(mA*ms)
Sleep	160.1X	0.03	4.80X
ADC sampling	0.1	2.31	0.23
Transmission	160	10.01	1601.6

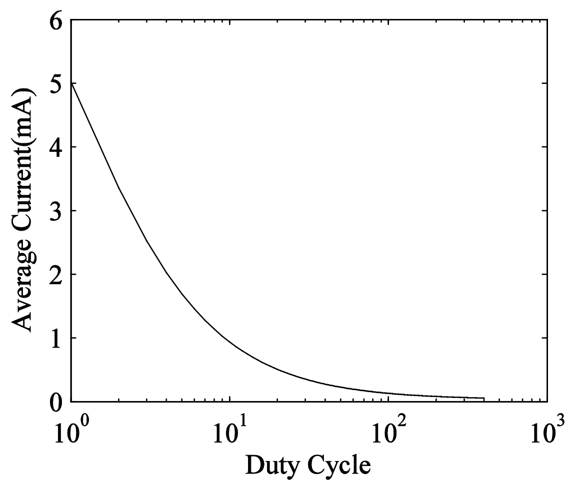

Figure 11. Time averaged current draw of the transmitter circuit vs. duty cycle

The maximium operational duration of the transmitter can be calculated using the average current data. Battery capacity (measured in mA-hr) is divided by the average current, yielding the maximum time in hours that the battery can source the required current. Using the average current results from Figure 11, the maximum operational lifetime of the transmitter circuit is plotted in Figure 12 for batteries with different capacity. The battery capacities shown in Figure 12 are typical of commercial off-the-shelf coin cell batteries. Table 2 highlights the duty cycle required to achieve a desired duration of operation, along with the time the transmitter spends sleeping for that duty cycle. For example, to power the transmitter for 1 year using a 560 mA-hr coin cell battery requires a duty cycle of 294, which means data will be acquired and transmitted about every 47 seconds for the entire year.

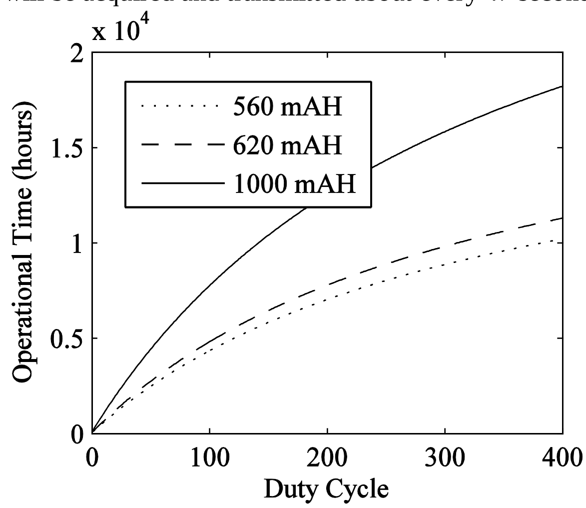

Figure 12. Predicted transmitter circuit operating time vs. duty cycle for different battery capacity

Table 2. Duty cycle and sleep duration for a desired transmitter circuit operating time for various battery capacities

	Duty Cycle ('Sleep' Time (sec))		
Operating Time	**560 mA-hr**	**620 mA-hr**	**1000 mA-hr**
1 week	3 (0.48)	2 (0.32)	2 (0.32)
2 weeks	6 (0.96)	5 (0.80)	3 (0.48)
1 month	12 (1.92)	11 (1.76)	6 (0.96)
½ year	91 (14.57)	80 (12.81)	45 (7.20)
1 year	294 (47.07)	244 (39.06)	118 (18.89)
2 years	5080 (813)	1851 (296)	368 (58.92)

The ability to remotely monitor the structural health of hydrokinetic turbine blades is of interest for two main applications. First, structural health data can provide service and maintenance personnel with much needed knowledge of the state of the blades, allowing timely repair and servicing before failure. Second, health data can aid environmental assessment studies of prototype machines, providing information on both the impact of the machine on the environment and the environment on the machine. In both cases, the investigated system will ideally enable faster future commercial deployment of hydrokinetic energy systems.

Results indicate that the data transmission system should be operated in different modes depending on the desired application. Specifically, the transmitter circuit should be operated with a duty cycle suited for the duration of the application. To achieve longer operational duration of the transmitter, a higher duty cycle is required. We anticipate that commercially deployed hydrokinetic machines will require long operational duration and thus high duty cycle, while shorter-term environment assessment and prototype studies will benefit from lower duty cycle operation. For example, environmental assessment testing of a prototype machine is a relatively short timeline on the order of days or weeks compared with a commerically deployed device that will be in water for years. Fast detection of changes in structural health are typically required for environment assessment (i.e., immediate detection of an impact), while more intermittent assessment of structural health can be tolerated with long-term deployed machines. Therefore, for short duration environmental assessment continuous max sampling should be used, providing a sample rate of 500 samples/sec. A 1000 mA-hr battery would last at most around 4 days at this rate. For a two-year deployment of a commercial system with a 1000 mA-hr battery, the transmission system should be operated with at least a duty cycle of 368 to provide a data sample about every 59 seconds.

4. Conclusions

The data transmission system can successfully communicate representative structural health data in a benchtop setting. Data can be transmitted acoustically underwater from an isolated source (transmitter, blade reference frame) to a static relay station (receiver, fixed reference frame), and then broadcast wirelessly to a remote monitoring station (via Bluetooth). Results indicate that the ultrasonic and Bluetooth communication performs flawlessly, and can transmit 10 bit data. However, error in the electronics measuring the structural health signal limit the accuracy of the measurements to ±5%.

The maximum rate at which the structural health data can be transmitted is 500 samples/sec. Each sample of structural health data is captured by the measurement electronics with 10 bit resolution, and the entire 10 bit data packet is transmitted. With our modified on-off keying encoding scheme, the underwater acoustic communication system must transmit a total of 16 bits: 10 data bits, 4 clock train bits, and 2 termination bits. With the 40 kHz acoustic frequency, each bit requires 0.125 ms, resulting in a total transmission time for 1 data sample of 2 ms. Thus, assuming continuous data transmission, a maximum rate of 500 samples per second can be achieved by the data transmission system.

The optimum mode of operation of the data transmission system is dependent on the hydrokinetic machine application. We examined application of the data transmission system to short term environmental impact testing of prototype hydrokinetic machines and long term commercially-deployed machines. For prototype testing, the desired goal of the data transmission system is to precisely record in real time the structural health and blade loading experienced under various conditions. This could include detailed strain response of the system over time, the response to impact or other transient events, and monitoring the evolution of the degradation and damage the blades experience. For prototype testing the data transmission system should operate at maximum sampling rate. Based on our analysis, max sampling rate could be achieved for 50+ hours of testing with any of the battery power sources described.

A commercially-deployed hydrokinetic system requires a longer lifetime than a prototype system. In this case, the data transmission system should make periodic structural health measurements, transmit the data, and then enter sleep mode to conserve power. While this mode of operation does not allow for "real-time" transient events to be monitored, it does extend the life of the monitoring system while still detecting deterioration and damage to the hydrokinetic blade. Based on our results, a data transmission system lifetime of two years can be achieved by increasing the duty cycle (sleep time) of the system. Using a relatively low capacity 560 mA-hr battery, a duty cycle of 5080 would provide operation for two years, and would measure the structural health data every 13 minutes 33 seconds throughout the 2 year period. If higher sampling rate is desired, a 1000 mA-hr battery could be used at a duty cycle of 368, which would acquire and transmit data every 59 seconds. Based on the capacity of the battery and duty cycle (sleep time) of the system, intermittent monitoring can be achieved for relatively long periods of time.

5. Future Work

The design, static benchtop testing, and characterization of the data transmission system for in-situ monitoring of composite blade structural health has been completed. However, over the next two months we plan to conduct dynamic testing of the system within a representative environment. For these tests we plan to mount the transmitter circuitry onto a smal-scale hydrokinetic turbine and then demonstrate data transmission while the system is in operation. Photographs of the prototype hydrokinetic turbine in the Missouri S&T water tunnel is shown in Figure 13.

Figure 13. Photographs of the water tunnel and prototype hydrokinetic turbine the data transmission system will be tested with over the next month.

The necessary electronic circuitry will be located in a dynamic water environment. The transmitter circuit will be in a waterproof housing and attached to the turbine shaft. While we envision a final design will place the sensitive electronics and ultrasonic transducer within the hub of the turbine assembly, initial tests will have these components secured external to the underwater hydrokinetic system. The transmitting ultrasonic transducer will be attatched at the stagnation point on the turbine hub, along its centerline. The receiver circuit and ultrasonic transducer will be statically mounted, fixed to the top support of the water tunnel. Data transmission from the rotating reference frame of the blade to the relay station and then to the remote monitoring computer will be demonstrated.

Acknowledgements

The authors wish to thank the Office of Naval Research (grant N00014-10-1-0923) and Department of Energy (grant DE-EE0004569) for supporting this work.

References

[1]Khan, M. J., Bhuyan, G., Iqbal, M. T., Quaicoe, J. E., "Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review," *Applied Energy*, Vol. 86, pp. 1823-1835, 2009.

[2]Khan, M. J., Iqbal, M. T., Quaicoe, J. E., "River current energy conversion systems: Progress, prospects and challenges," *Renewable and Sustainable Energy Reviews*, Vol. 12, pp. 2177-2193, 2008.

[3]Haas, K. A., Fritz, H. M., French, S. P., Smith, B. T., Neary, V., "Assessment of Energy Production Potential from Tidal Streams in the United States," Final Project Report, DE-FG36-08GO18174, Georgia Tech Research Corporation, June 29, 2011.

[4]Scott, G., "Mapping and Assessment of the United States Ocean Wave Energy Resource," Final Report, 1024637, Electric Power Research Institute, Dec. 2011.

[5]Asmus, P., Wheelock, C., "Hydrokinetic and Ocean Energy: Renewable Power Generation from Ocean Wave, Tidal Stream, River Hydrokinetic, Ocean Current, and Ocean Thermal Technologies," Market Research Report, Pike Research, 2009.

[6]Previsic, M., "System Level Design, Performance, Cost and Economic Assessment - Alaska River In-Stream Power Plants," EPRI RP 006 Alaska Electric Power Research Institute, Oct. 31, 2008.

[7]"Hydrokinetic Electric Power Generation," Climate TechBook, Pew Center on Global Climate Change, Dec. 2009.

[8]Walford, C. A., "Wind Turbine Reliability: Understanding and Minimizing Wind Turbine Operation and Maintenance Costs," Sandia Report SAND2006-1100, Prepared by Global Energy Concepts, LLC, Mar. 2006.

[9]"Report to Congress on the Potential Environmental Effects of Marine and Hydrokinetic Energy Technologies," U.S. Dept. of Energy, Dec. 2009.

[10]Sale, M. J., Cada, G. F., Acker, T. L., Carlson, T., Dauble, D. D., et al., "DOE Hydropower Program Biennial Report for FY 2005-2006," ORNL/TM-2006/97, U.S. Dept. of Energy, July 2006.

[11]Cada, G., Ahlgrimm, J., Bahleda, M., Bigford, T., Stavrakas, S. D., et al., "Potential Impacts of Hydrokinetic and Wave energy Conversion Technologies on Aquatic environments," *Fisheries*, Vol. 32, No. 4, pp. 174-181, April 2007.

[12]Coutant, C. C., Cada., G. F., "What's the future of instream hydro?," *Hydro Review XXIV*, Vol. 6, pp. 42-49, 2005.

[13]Ciang, C. C., Lee, J.-R., Bang, H.-J., "Structural health monitoring for a wind turbine system: a review of damage detection methods," *Measurement Science and Technology*, Vol. 19, pp. 122001, 2008.

[14]Dutton, A. G., Blanch, M. J., Vionis, P., Lekou, D., Delft, D. R. V. v., et al., "Acoustic Emission Condition Monitoring of Wind Turbine Rotor Blades: Laboratory Certification Testing to Large Scale In-Service Deployment," *European Wind Energy Conference - EWEC*, Madrid, Spain, 2003.

[15]M.J.Blanch, A.G.Dutton, "Acoustic Emission Monitoring of Field Tests of an operating Wind Turbine," *Key Engineering Materials*, Vol. 245-246, pp. 475-482, July 2003.

[16]Akyildiz, I. F., Pompili, D., Melodia, T., "Underwater acoustic sensor networks: research challenges," *Ad Hoc Networks*, Vol. 3, pp. 257-279, 2005.

[17]Robison, K., Watkins, S. E., Nicholas, J., Chandrashekhara, K., Rovey, J. L., "Instrumented Composite Turbine Blade for Health Monitoring," *SPIE Smart Structures and Materials, Non-destructive Evaluation, and Health Monitoring Conference*, San Diego, CA, Mar. 11-15, 2012.

[18]H. C. Pumphrey, L. A. Crum and L. Bjorno, "Underwater sound produced by individual drop impacts and rainfall," *JASA*, vol 4, no. 4, April 1989

[19R. B. Mitsen, "Underwater Noise of Research Vessels: Review and Recommendations," International Council for the Exploration of the Sea, Copenhagen, Denmark, May 1995.

[20] M. A. Ainslie, J. G. McColm, "A simplified formula for viscous and chemical absorption in seawater," *J. Acoust. Soc. Am.*,vol 103, no. 3, March 1998

[21]Chuan Li, D. A. Hutchins, R. J. Green, "Short-Range Ultrasonic Digital Communications in Air," \ *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol 55, no. 4, April 2008