

Experimental Study of Polymer Bearings

For use in Hydrokinetic Devices

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Introduction

With the decreasing presence of fuel reserves and the increasing need for power in today's world, the development of clean renewable energy has never been more important. Hydrokinetic power producing devices are one of the many sources of renewable energy that have shown the potential to help alleviate some of the world's power needs. However, hydrokinetic power producing devices are still a very young technology that still needs further development in order to become economically feasible, environmentally friendly, and physically practical. Hydrokinetic power producing devices are subjected to harsh conditions (such as high pressures, low temperatures, remote areas, and presence of high amounts of sediment) that pose as a challenge to current technology.

The bearing and shaft assembly is an integral part of hydrokinetic power producing devices. The strength of bearings under load on a shaft is an item of particular interest as wear due to abrasion can affect the efficiency of the entire system. Engineered polymers materials are becoming popular choice for such bearings as they can cost less, weigh less, and self-lubricate. It is important to investigate the abrasive characteristics and lifecycle of these polymer bearings in order to optimize efficiency.

In 2012, Professor Muhammad Ali led a research project supported/assisted by the Ocean Renewable Power Company (ORPC); a Maine based renewable energy company that specializes in the development of ocean and river power producing technology. Dr. Ali was also assisted by fellow UAA School of Engineering faculty members (including Professor Jeff Hoffman and Professor Todd Peterson). The project consisted of designing and building a closed flume with two test stations for testing bearings that are used on hydrokinetic devices. Four bearings made of different material types were investigated to observe the abrasive effects that occur underwater and to quantify the coefficients of friction for each type of bearing. The results of this study, "Experimental Study of Abrasion Characteristics for Critical Sliding Components for use in Hydrokinetic Devices", was published in the International Journal of Renewable Energy. Dr. Ali left UAA and the test apparatus and study was put on hiatus.

The original test apparatus' test stations consisted of three bearings mounted in-line on a shaft connected to a motor assembly, shown in Figure 1. The outer bearings were in a fixed position and a force was applied to the middle bearing. The bearings were incorporated within the flume and the motor was placed outside of the flume, the shaft penetrated the test station via mechanical seals. The original testing configuration had a couple issues/concerns. The reactive force created on each of the outer bearings was half of the force exerted on the middle bearing. To find the coefficient of friction of the bearings, the assumption had to be made that the COF varied with the applied load in a linear manner. This is a point of concern as this assumption creates uncertainty in the quantification of the coefficient of friction. Another point of concern was the mechanical seals that were used to encapsulate the bearing and shaft assembly within the flume. The mechanical seals used are very expensive and impractical to replace.

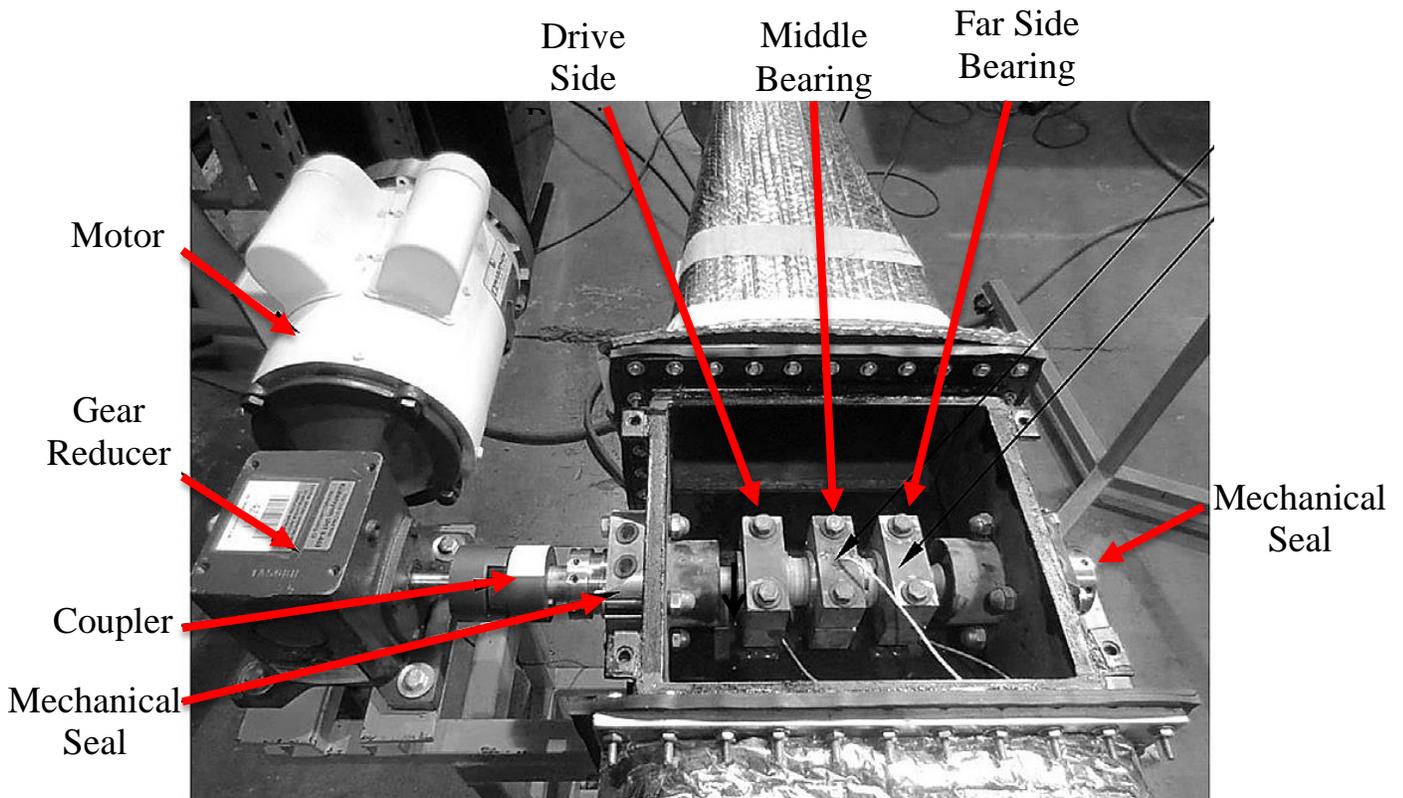


Figure 1: View of original test station

With the original test apparatus still in working condition, this study had the opportunity to be continued and improved. Design changes to the original test section allowed the aforementioned concerns with the original apparatus' configuration to be eliminated.

Project Statement

ORPC and UAA continued the study of the abrasive characteristics of bearing and shaft assemblies within hydrokinetic devices. In order to improve this study, the test sections from the 2012 study's apparatus were redesigned to reduce extraneous variables, eliminate unnecessary components, and accommodate new bearings. The coefficient of friction, abrasive characteristics between hydrokinetic bearings and shafts, and the overall bearing lifecycle was studied more accurately with an improved test section. One new set of bearings was tested for this project.

Scope of Work

The scope of this project will include the following items:

- 1) Recommissioning the original testing apparatus (flume).

The flume had been inactive since 2012 and required cleaning and maintenance. The apparatus was put back into working condition in order to continue further bearing studies.

- 2) Redesign the testing station to include 4 bearings.

The testing section's original 3 bearing configuration created complications and extraneous variables that increased the uncertainty in test results. UAA redesigned the bearing testing chambers to accommodate a 4 bearing configuration and new bearings. Fabrication ready drawings were created by ORPC with the assistance of UAA.

- 3) Replace the mechanical seals with lip seals.

The mechanical seals used in the 2012 study were difficult to replace and expensive. UAA redesigned the testing chamber with a configuration that includes lip seals which are easier and cheaper to replace.

- 4) Design new hydrokinetic device bearings and shafts.

ORPC designed two new sets of bearings and shafts to be tested. UAA worked with ORPC to design the testing station to accommodate the new bearings.

- 5) Manufacture new testing station and bearing shaft assemblies.

New testing stations were fabricated, assembled, and incorporated into the flume. The manufacturing of the test station components was done by UAA. Bearing and shaft manufacturing was coordinated by ORPC.

- 6) Run 60 hour load test on one set of bearings.

One set of the newly designed bearing and shaft assemblies were tested and the wear rates were described. The coefficient of friction as a function of time of this bearing assembly was obtained through the 60 hour load test in clear water. Along with measuring the behavior of friction, an estimate of total expected life was determined.

The scope of this project does not include redesigning any other portion of the flume testing apparatus. Although it may be of future interest, the abrasion characteristics of the hydrokinetic bearings in sediment rich water was not examined.

Methods

Test Apparatus Design

To test new hydrokinetic bearings, a custom test apparatus was used that was designed and built in the previous 2012 study. This apparatus includes two testing stations, a flowmeter, a custom built heat exchanger, and pump. Figure 2 shows a process diagram of the flume system and Figure 3 shows a picture of the actual flume.

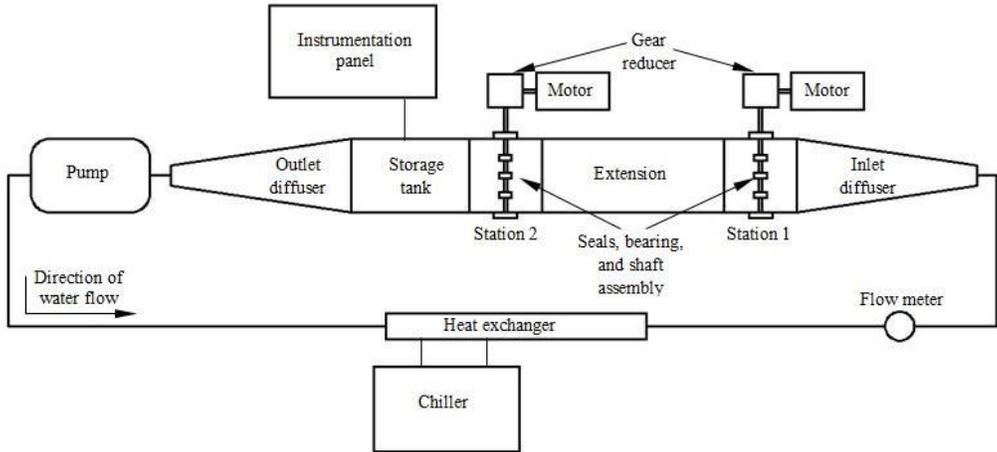


Figure 2: Process flow diagram of the flume apparatus.

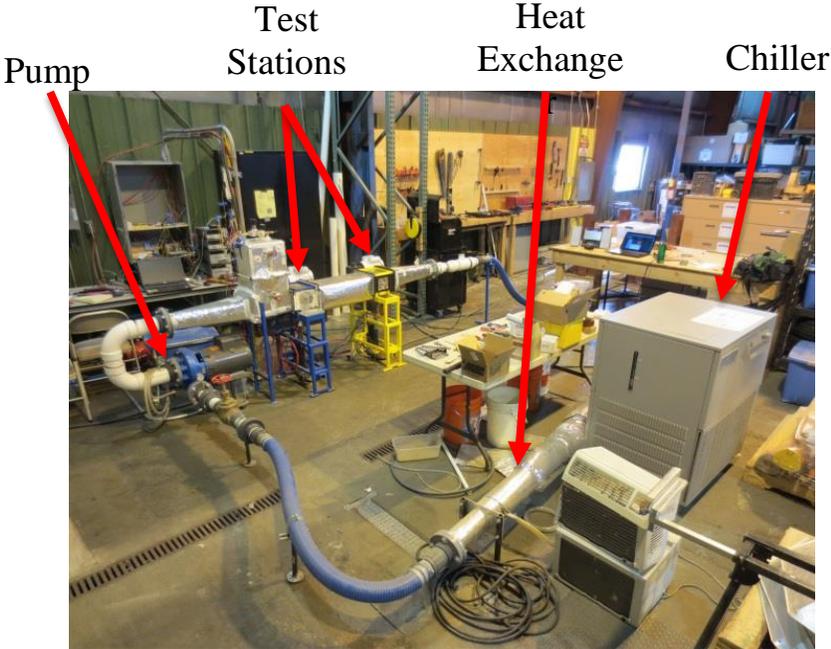


Figure 3: View of the entire flume apparatus.

For the purposes of this study, the testing stations were the only components of the flume apparatus that required redesign in order to properly measure the coefficient of friction on the hydrokinetic bearings. The test section with a three bearing configuration from the 2012 study can be seen in Figure 4.

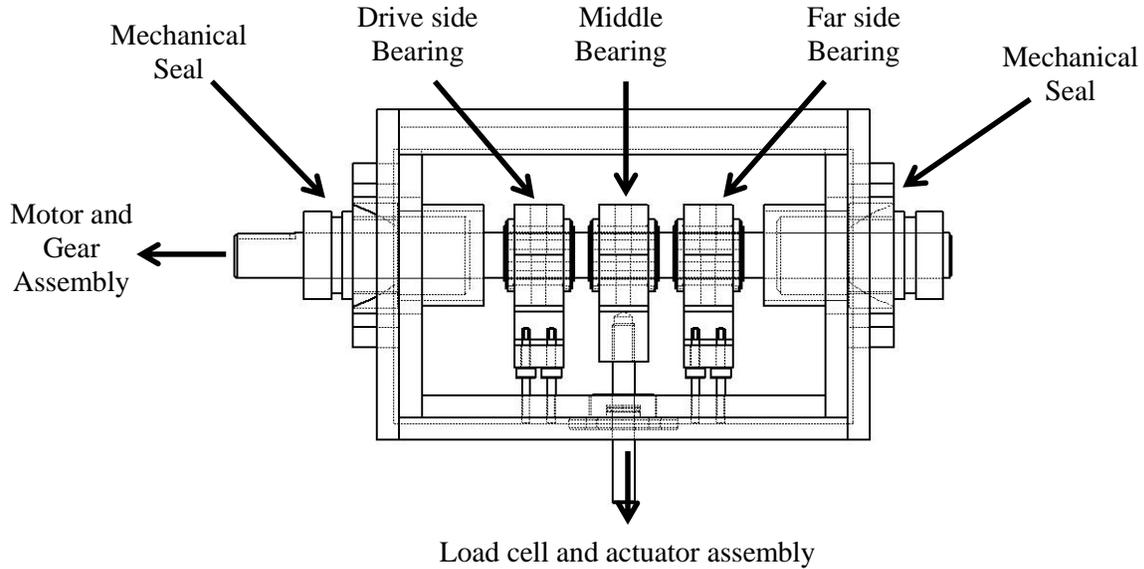


Figure 4: The cross-sectional view of a single test station from the 2012 study.

This three bearing configuration required use of an indeterminate problem to determine the coefficient of friction. This is stemmed from the behavior of the static loading relationship between the three bearings. As can be seen in Figure 5A, the center bearing load (F) in the three bearing configuration resulted in a reactive force ($F/2$) half of the applied load in the outer bearings. This created difficulties in properly quantifying the coefficient of friction of these bearings. The assumption had to be made that the COF varied linearly with the amount of load put on the center bearing. This assumption generated uncertainties in the 2012 study. The four bearing configuration was determined to be a better design than the three bearing configuration based on the simple behavior of its static loading. This is shown in Figure 5B, the four bearing configuration results in an equal amount of force applied to each bearing.

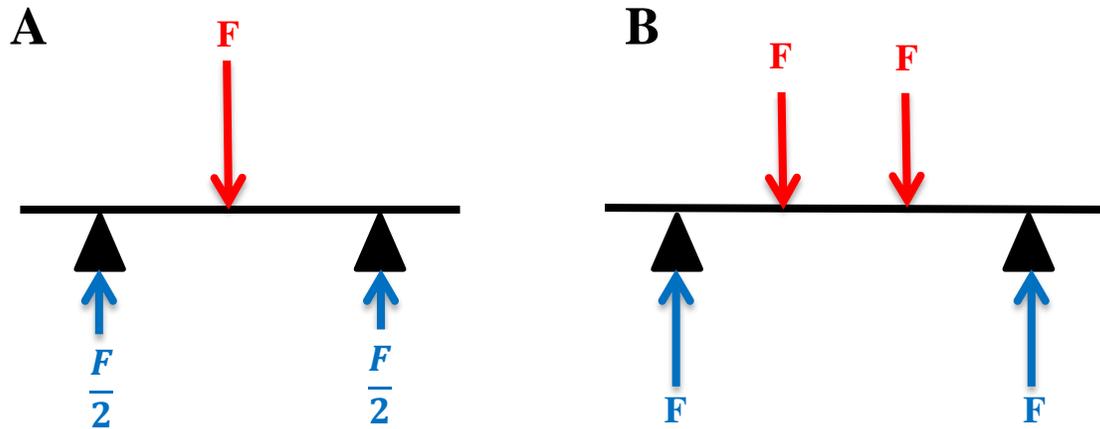


Figure 5: Simplified static loading behavior of the three bearing configuration (A) and the four bearing configuration (B).

After coming to the conclusion that the four bearing configuration was better for this application the redesigning process began. The original CAD models of the flume were available and were utilized. However the flume had been sitting since 2012, so the CAD model had to be dimensionally verified and updated. Once that was done, UAA and ORPC worked together to redesign the test station. ORPC designed the new bearings to be tested so that they could properly work in the new four bearing configuration. Another consideration made when redesigning the test stations was eliminating the expensive and impractical mechanical seals. These mechanical seals were replaced with a simple custom made flange and double lip seal assembly. This double lip seal design was considerably less expensive, easier to install, and easily adjustable. The newly redesigned testing station with a four bearing configuration and double lip seal is shown in Figure 6.

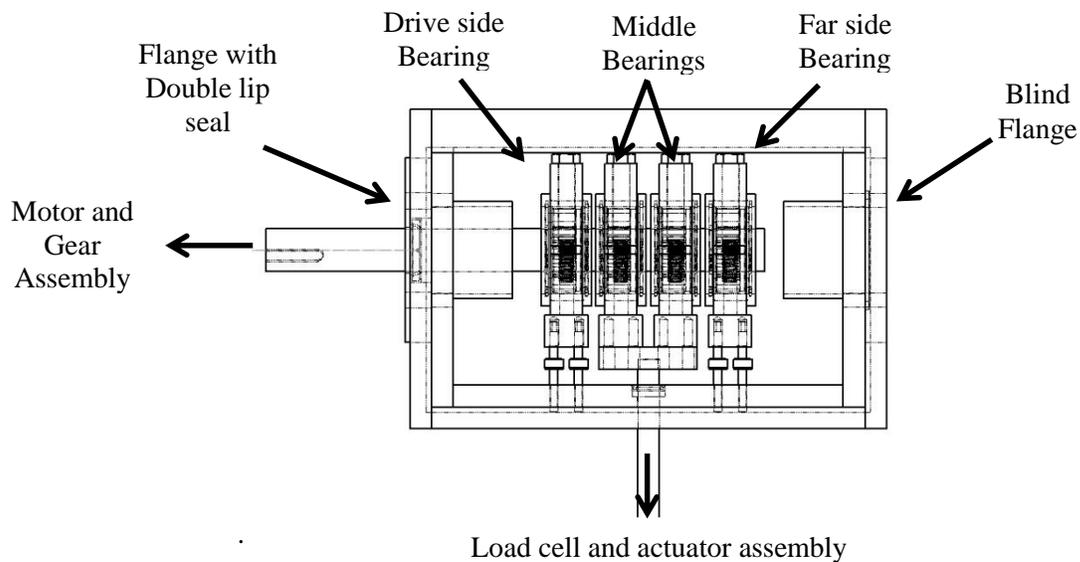


Figure 6: The cross-sectional view of the newly designed test station.

Load Application Design

The flume testing apparatus from 2012 used an electro-hydraulic actuator to apply a load to the middle bearing with a load cell in the middle to record the applied load. The configuration that was originally used can be seen in Figure 7.

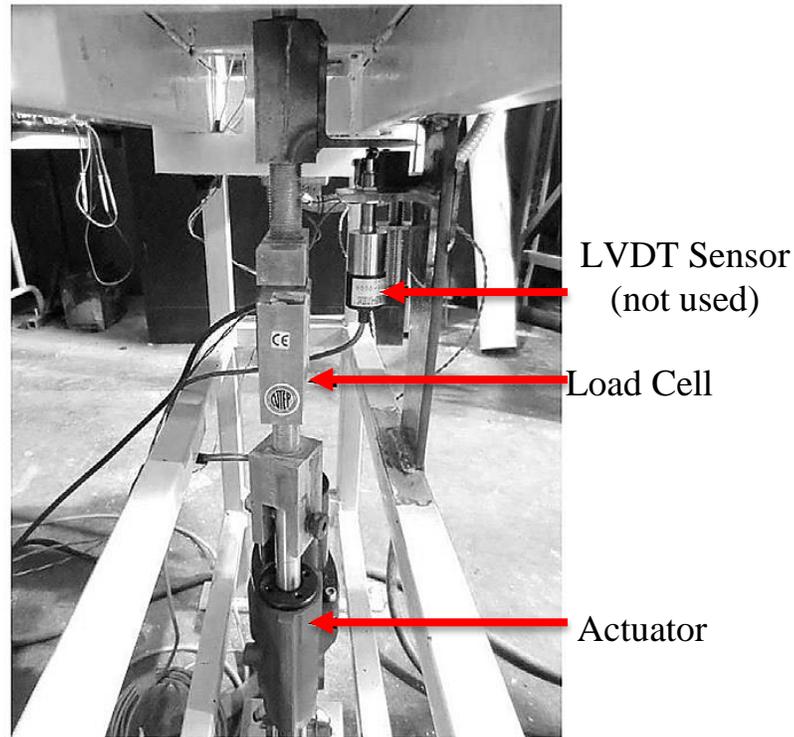


Figure 7: Hydraulic actuator with load cell assembly from 2012 study.

After ORPC established the loads required to properly test the new bearings (all less than 500 lb.), it became clear that the electro-hydraulic actuator would not be adequate for this test. The loads that the test required were far less than the actuator was capable of providing. Additionally, the actuator had a tendency to drift. A new assembly was created to replace the actuator. The new assembly can be seen in Figure 8.

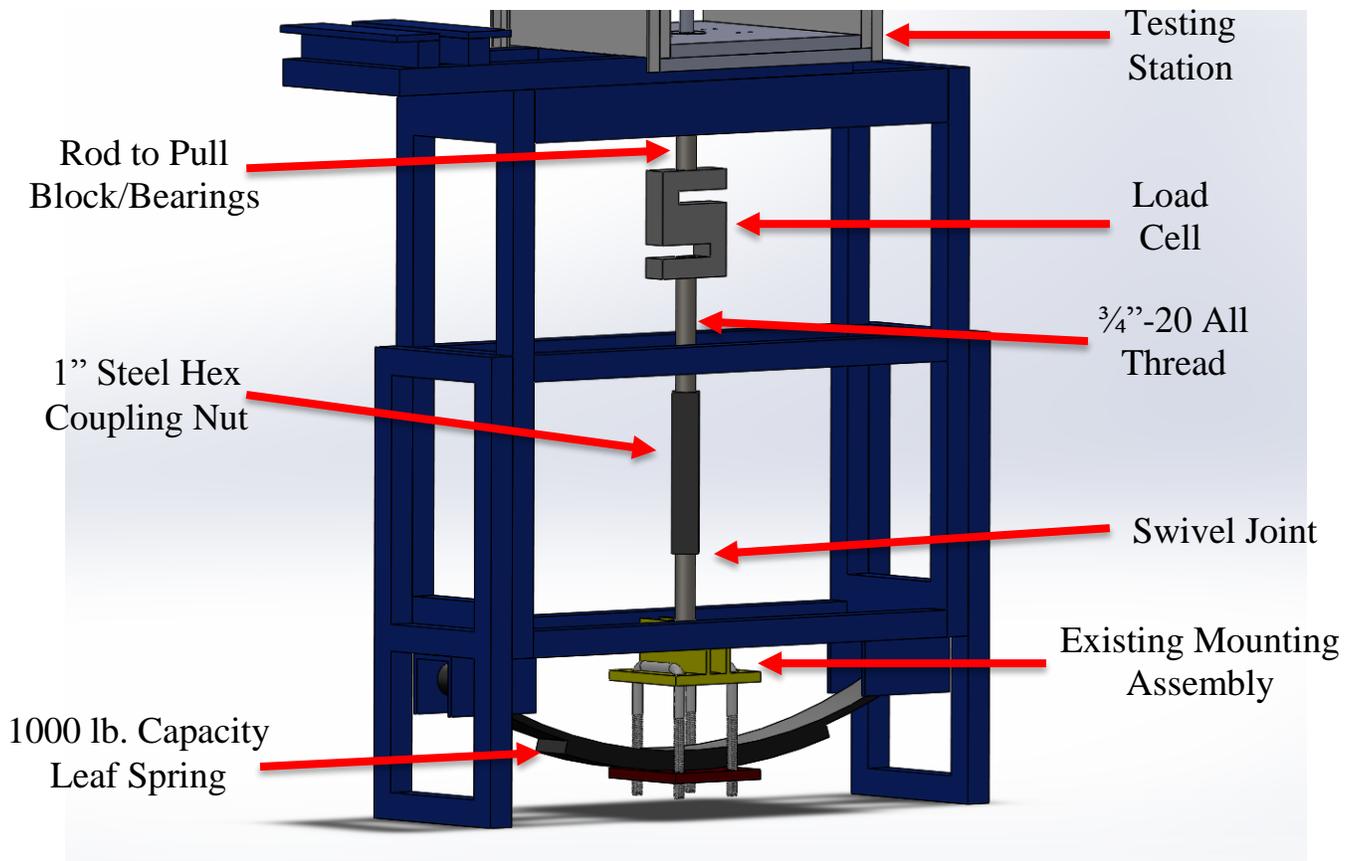


Figure 8: New load application assembly.

The two pieces of $\frac{3}{4}$ " all thread was connected using a coupling nut made from 1"x1" steel hex bar with tapped holes. The rod on the bottom of this assembly was given a swivel joint so that when the coupling nut was rotated it would pull the upper half down, thus creating the load. This new assembly had the benefit of being easily adjusted and prevented the load from drifting. The leaf spring and mounting assembly on the bottom were existing parts from the 2012 apparatus/study that were reused.

Bearing Design

The primary interest in this study is the affect that different polymers have on the performance of hydrokinetic bearings; in particular, the coefficient of friction and durability associated with different polymers. ORPC took on the design of the bearings and bearing mounts. Unlike the plain bearings that were tested in 2012, ORPC decided to design roller bearings. Roller bearings are more commonly used for the application of hydrokinetic power producing devices. ORPC used their expertise in hydrokinetic bearings and knowledge of technological advances in polymers to come up with two bearing designs, shown in Figure 9 and 10 with their mounting holders.

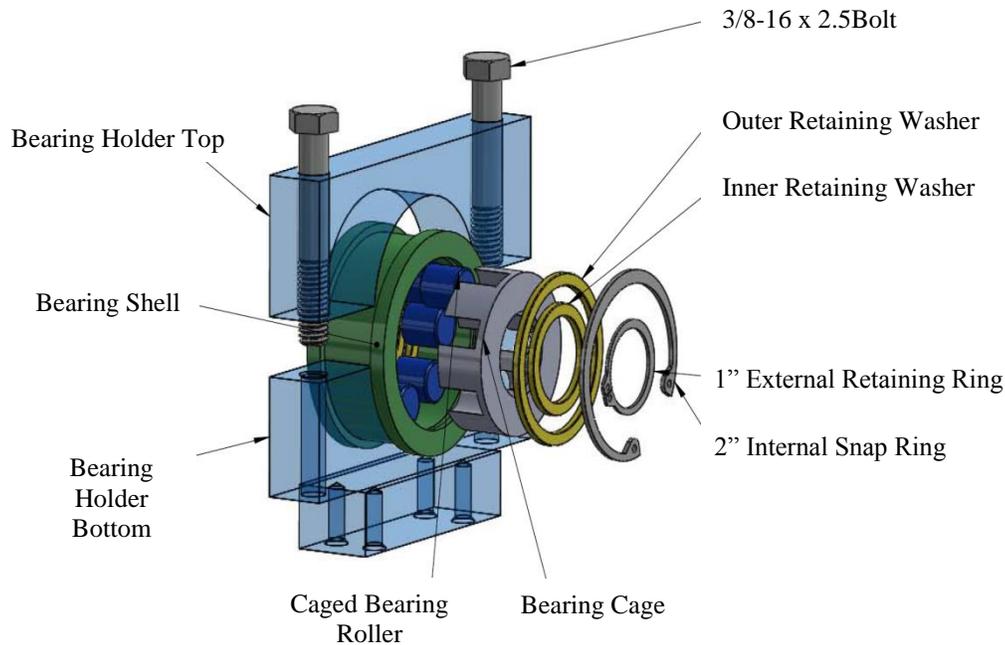


Figure 9: Exploded view of bearing design with bearing cage (caged).

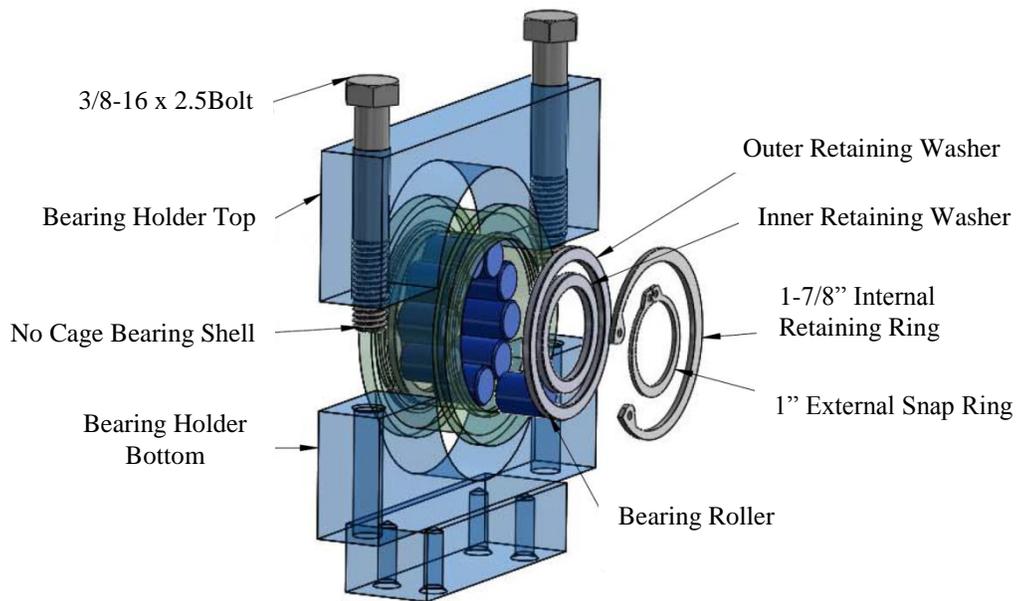


Figure 10: Exploded view of bearing design without bearing cage (full complement).

The primary difference between the two bearing designs is the presence of a bearing cage. These bearings are primarily comprised of stainless steel. However the critical sliding components, the bearing rollers and bearing roller cages, were made of a polyamide-imide known as Torlon. Torlon is a polymer that has high strength, high heat capability, and wide-ranging chemical resistance. Three types of Torlon were examined in this study: 4301, 4302, and 7130. These different types of Torlon were used in multiple

configurations to produce a variety of bearings. A comparative analysis of the bearings was conducted to determine which has the longest life cycle.

Vibration Analysis

Along with determining the behavior of friction, an estimate of the total expected lifecycle of the bearings was examined. The lifecycle of the bearing is established by determining the point at which it fails. The problem then arises: what is considered failure? Running the bearing under load until a bearing roller or cage breaks and the entire bearing seizes up is impractical and unsafe. The best way to determine failure is via vibration analysis. Vibration analysis is a common method of analyzing failure within rotating machinery and has been utilized for over three decades.

Accelerometers were mounted to each bearing holder. Using a Fourier transform, the accelerometer's transmitted data in the time domain was transformed into a more easily understood frequency domain. An example of a Fourier transform can be seen in Figure 11 and 12 (please note that these waveforms are not from test data).

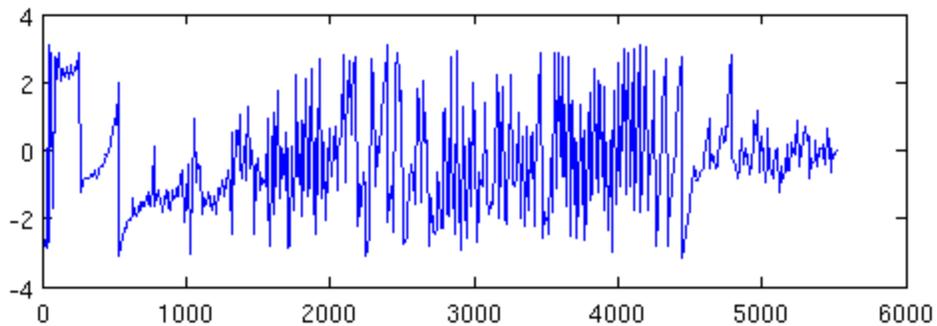


Figure 11: Accelerometer Data Example (Time vs. Magnitude)

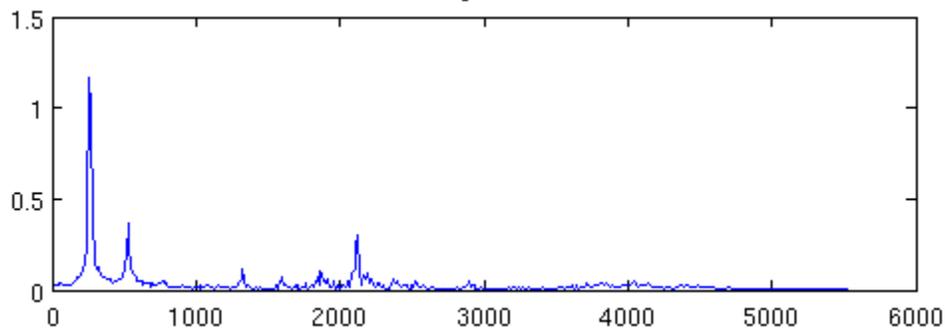


Figure 12: Fourier Transform Example (Frequency vs. Magnitude)

Figure 11 shows an example of the data that the accelerometer captured. When a Fourier transform is conducted, the data is put into the frequency domain, as shown in Figure 12. The “peaks” within the frequency domain waveform are of particular interest for vibration analysis.

A digital oscilloscope was used to conduct the Fourier Transform in real time with a sample rate higher than the necessary 50 MHz. At the beginning of the test, a baseline “snapshot” was taken of the

frequency domain waveform. From that point, the waveform was checked periodically to observe if it had changed. In particular, if the “peaks” within the waveform increased in magnitude or new “peaks” appeared, it indicated an increase in vibration. Bearing failure was determined if the “peaks” within the waveform increased in magnitude by 50%.

The accelerometers used were a rugged, general purpose underwater, biaxial accelerometer manufactured by Meggitt Sensing Systems, the Wilcoxon Research model 757. Due to the size of these accelerometers, it took some creativity to fit them within the small area of the test station. The accelerometer configuration that was determined to be the most effective and practical can be seen in Figure 13.

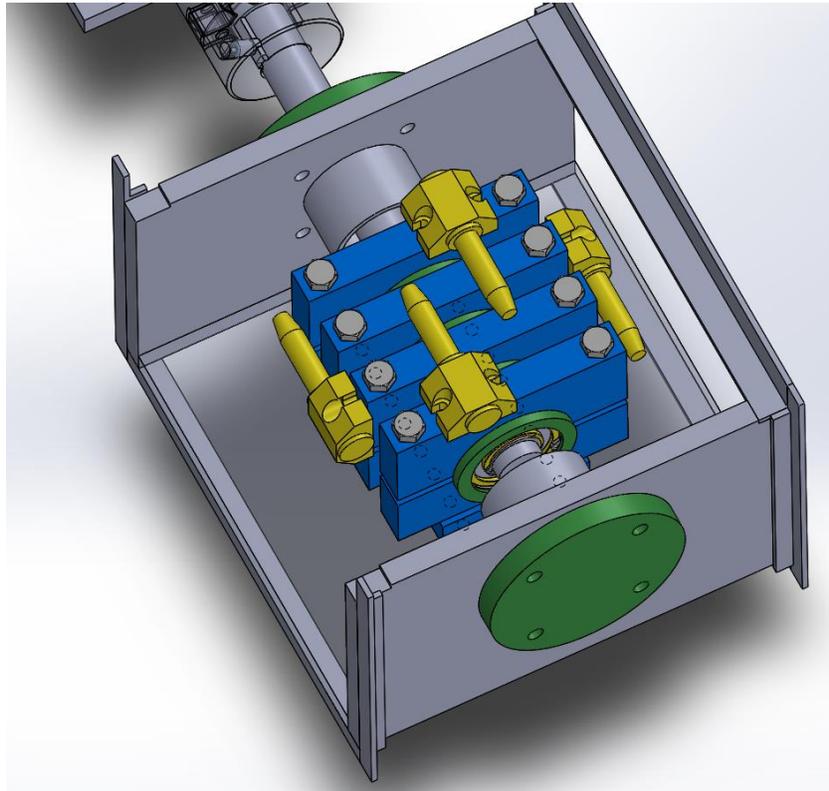


Figure 13: Accelerometer configuration within test station.

General Apparatus Set-up and Testing Procedures

Prior to testing, the floor of each test section was machined to a flatness of $\pm 0.002''$. Shims and alignment pins were used to verify that all the bearings are properly in-line. Prior to coupling the shaft to the motor, a dial indicator was used to verify radial run out in addition to insuring the shaft rotates freely by hand. These measures were taken to insure that the shaft was in proper alignment with the bearings and motor coupling.

Two test stations were utilized during the bearing testing. Table 1 shows the configuration of the different types of Torlon within the bearings and the arrangement within the two test stations.

Table 1: Test Matrix (Bearings tested)

Upstream Arrangement (4000 series Torlon)	Bearing and cage material type	Materials Description
Bearing 1 (F2)	4301 with 4301 all same	Slick and slick
Bearing 2 (C2)	4301 with 4301 cage	Slickest everything
Bearing 3 (C3)	4203 with 4301 cage	Pretty strong roller with slick cage
Bearing 4 (F3)	4203 with 4301	Medium strength and slick alternating
Downstream Arrangement (7139 series Torlon)		
Bearing 1 (F1)	7130 all bearings	Strongest rollers full complement
Bearing 2 (C4)	7130 with 4203 cage	Strongest roller with med strong cage
Bearing 3 (C1)	7130 with 4301 cage	Strongest roller with slickest cage
Bearing 4 (F5)	7130 with 4301	Strong and slick alternating

The bearing rollers were examined before and after the test to quantify wear. In addition to physical size measurements, the initial mass of the roller sets was documented and repeated at the end of the testing. Using this information, the amount of material worn off was calculated. The condition of the contact surfaces was captured with images. In addition to examining the bearing rollers, the shafts were also physically measured for excessive wear using a dial indicator translated along the shaft's length.

General Flume Procedure for 60 Hour Tests:

1. Set up Data Acquisition: Turn on power supplies and multimeter, run LabVIEW.
2. Run flume with clear tap water removing excess water until the water is free of sediment as noted in a 5 gallon clear container.
3. Fill Flume with water (clean tap water).
4. Turn on pump.
5. Turn on shaft motor.
6. Apply load with hydraulic actuator.
7. Begin data recording and note time, test name, operator name, etc.

Shut Down:

1. Record shut down time.
2. Stop data acquisition.
3. Remove Actuator Load.
4. Stop the Motor.
5. Stop the Pump.

Periodically, every 30 minutes or so, the apparatus was checked for indications that bearings or seals were wearing out. The accelerometers/oscilloscope was also monitored for increased vibration, which could also be a sign that increased wear is occurring. The seals constantly checked to notice if any leaking is taking place. Finally, the voltage coming off of the load cell was checked often.

General Operating Conditions

The bearing test was conducted under the general operating conditions outlined in Table 2.

Table 2: General operating conditions

Condition	Value	Unit
Shaft Speed	300	RPM
Flow	300	gal/min
Water Condition (Turbidity)	0	lb./gal
Water Temperature	60-68	°F
Total Test Time	60	Hr.

The speed of the shaft was monitored and maintained using a stroboscope/tachometer located at the coupling connecting the gear reducer to the bearing shaft. The flow of water was induced using a Gould's 3656 centrifugal pump and adjusted to the proper rate using a gate valve. This flow was monitored using a Blue White Industries flow rate sensor. The water was clear, clean tap water for the 60 hour test, a sample was taken to verify it is clear of sediment. The heat exchanger that is incorporated in the flume was not used. The temperature of the water had been concluded (from Dr. Ali's 2012 Test) to be an insignificant variable to the bearing's COF in this test. The building's ambient temperature maintained the water at a temperature between 60 and 68°F. The water temperature was still monitored (to ensure consistency), but was not recorded. The hydrokinetic bearing test was designed to simulate 60 in-field hours bearing use. Due to the flume needing constant supervision while operating, the testing occurred in 8 hour increments with approximately 16 hour breaks in between.

Bearing Loads

As mentioned earlier, the test conditions had been designed around 60 hours of in-field use for full size bearings. The bearing rollers that were tested experience a load once every full revolution in which it takes three rotations of the shaft for the roller to complete a full revolution. With this in mind, it was approximated that in 1 hour at 300 rpm the bearing roller surface undergoes 6×10^3 load cycles. Using this information ORPC devised a load application test plan for the entire 60 hour test. Table 3 outlines the loads applied, load duration within the 60 hour test, and the relationship to cycle life.

Table 3: Applied Loads

Bearing Type	Applied Force (lbf)	Time (hours)	Cycle Life Details
4000 Series Torlon			
	30	5	near 10 ⁷ cycle life for 43 series material - Caged
	40	5	near 10 ⁷ cycle life for 42 series material – Full compliment
	55	10	near 10 ⁶ cycle life for 43 series material - Caged
	70	10	near 10 ⁶ cycle life for 42 series material – Full compliment
	100	15	near 10 ⁵ cycle life for 43 series material - Caged
	135	15	near 10 ⁵ cycle life for 42 series material – Full compliment
7139 Series Torlon			
	90	5	Near 10 ⁷ cycle life for 71 series material - Caged.
	120	5	near 10 ⁷ cycle life for 71 series material – Full compliment
	120	10	near 10 ⁶ cycle life for 71 series material - Caged
	160	10	near 10 ⁶ cycle life for 71 series material – Full compliment
	185	15	near 10 ⁵ cycle life for 71 series material - Caged
	250	15	near 10 ⁵ cycle life for 71 series material – Full compliment

Test Measurements

Measurements of the shaft speed, power into shaft motor, applied load, water condition, and vibration were recorded during the test, see Table 4 for details.

Table 4: Recorded Measurements.

Measurement Taken	Unit	Method
Shaft Speed	RPM	LabVIEW with stroboscope
Power Into Shaft Motor	Watts	Power Meter
Applied load	lbs.	Load cell with LabVIEW
Water Condition (Turbidity)	Lbs./gal	Turbidity Sensor & Sample measurement
Vibration		Oscilloscope with X and Y accelerometers

The speed of the bearing shaft was recorded using LabVIEW connected to a stroboscope. The applied load was recorded using LabVIEW with a load cell attached to the middle two bearings assembly, this load cell assembly is shown in Figures 7 and 8. The power into the shaft was calculated from the current and voltage into the motor. Screenshots of the digital oscilloscope connected to the accelerometers was taken periodically to monitor vibration, as mentioned earlier.

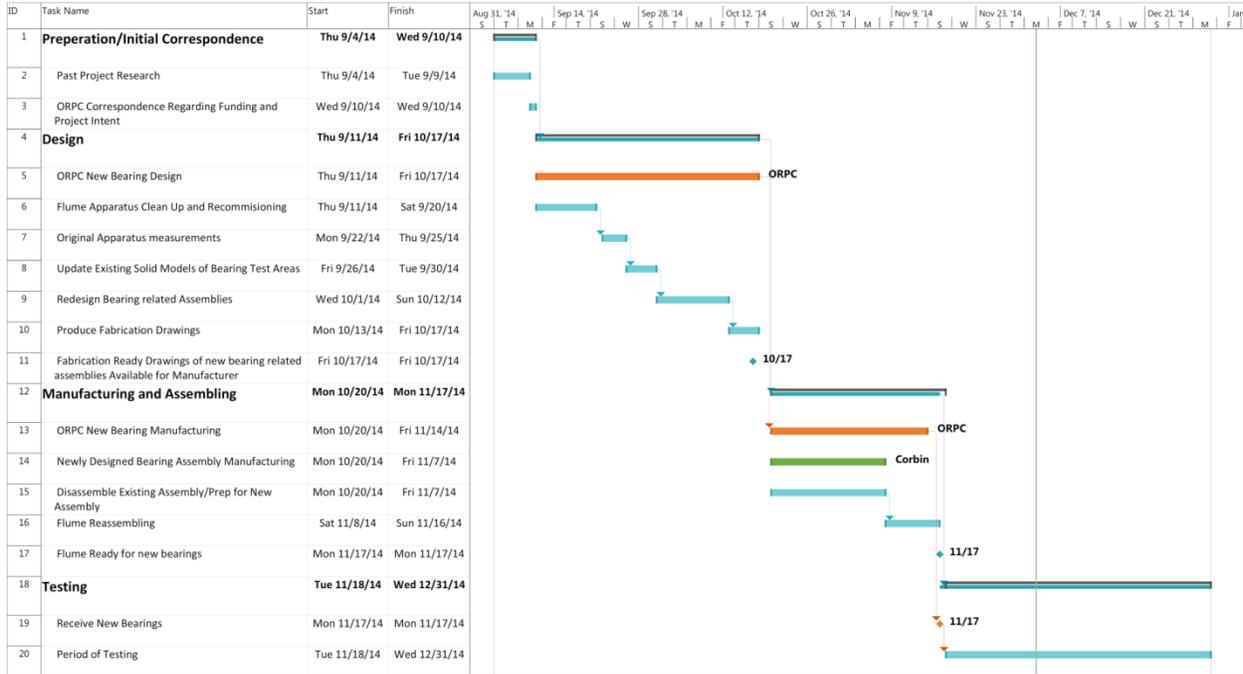
Conclusion

The test apparatus from Dr. Ali's 2012 study on hydrokinetic bearings has been redesigned to better evaluate the coefficient of friction, abrasive characteristics between hydrokinetic bearings and shafts, and the overall lifecycle of hydrokinetic bearings. The transition from a 3 bearing configuration to a 4 bearing configuration allows an extraneous variable to be eliminated, thus making the test more accurate. Replacement of the mechanical seals with lip seals drastically decreased the cost of parts and also allowed for easier assembly. With the elimination of the electro-hydraulic actuator, the load applied to the bearings is much easier to control. The design of the bearings, bearing shaft, and bearing mounts done by ORPC allowed the flume to be utilized to test hydrokinetic bearings of their interest and to determine which design is best. Inclusion of vibration analysis within the study allows for an accurate study of the lifecycle of the bearings. The method of testing has been outlined and the bearings are ready to be tested. Unfortunately, due to long lead times on critical items such as the bearings and bearing shafts, a 60 hour test was unable to be conducted. It was hoped to have done a test on one set of new bearings but was not necessarily expected.

All aspects of the test apparatus and testing methods have been designed and the test on new bearings is ready to begin. The flume is being reconstructed and the bearing test will commence soon. It is anticipated to test two sets of bearings, one in clean water and one in sediment rich water by the end of December 2014. After the testing is complete and all data is properly processed, the information will be given to ORPC to submit to the Department of Energy as required for their grant. It is ORPC's hope to continue this grant and study so that they can further their knowledge on efficient hydrokinetic bearings. Also, UAA hopes to continue work with ORPC after the completion of this project on more graduate level studies regarding hydrokinetic bearings.

The redesigned test apparatus allows for ORPC to continue developing a more efficient hydrokinetic bearing. It is important to develop bearings that run with less friction and longer lifecycles as maintenance on hydrokinetic devices is a significant factor in the cost of these devices. Making hydrokinetic devices more economically feasible will help the world transition away from fossil fuels into greatly needed clean renewable energy.

Project Schedule



Project Budget

ORPC was issued a grant by the U.S. Department of Energy to conduct this study. ORPC was responsible for the design and manufacturing of the bearings, bearing mounts, and bearing shaft. It was UAA’s responsibility to design and furnish the test apparatus to be used as well as to conduct the testing of the bearings.

The total budget for UAA’s contribution to this test is \$21,407. In terms of labor, this estimate is for student labor only as Drs. Petersen and Hoffman are advising as part of our current contract with UAA. A breakdown of costs associated with this estimate is provided below.

Item	Associated Cost	Details
Materials	\$ 5,049	Supplies needed to upgrade flume. This excludes fabrication of bearings.
Labor	\$ 8,433	450 man hour at \$18.74/hour
Fringe	\$ 691	8.2%
Indirect	\$ 7,234	51.2%
TOTAL	\$ 21,407	

Resources

- UAA Senior Design Studio.
- Dr. Ali et. al. previously built flume for testing.
- Corbin and the UAA machine shop.
- ORPC Design team.

References

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