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Developing an Instrumentation Package for in-Water Testing of Marine Hydrokinetic Energy Devices

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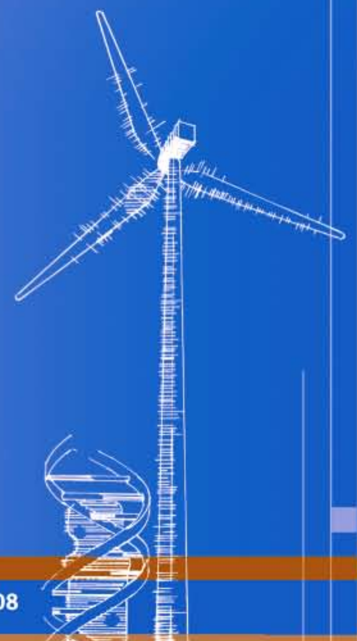

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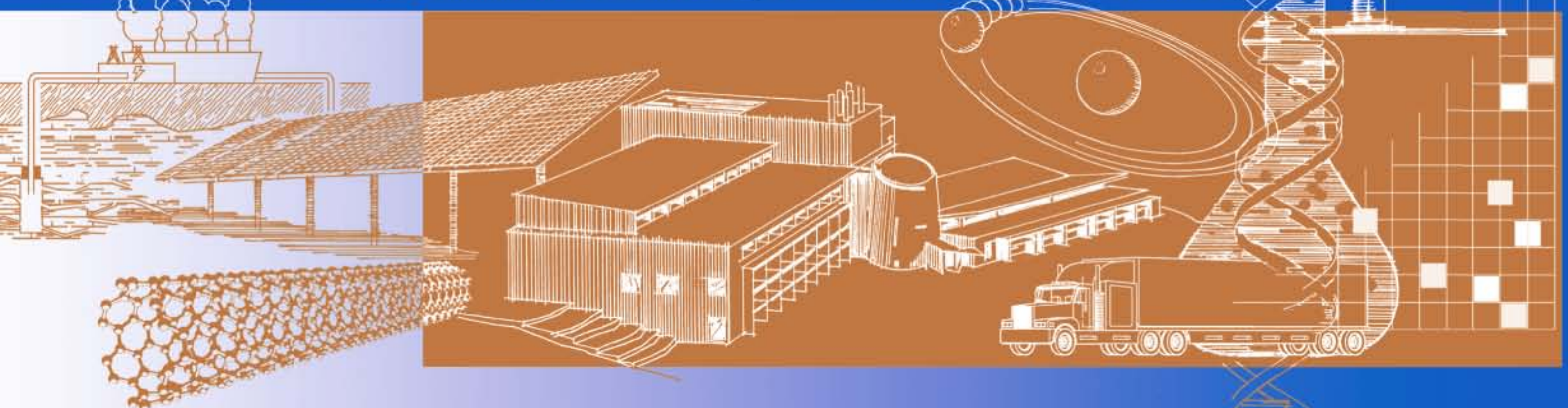

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Developing an Instrumentation Package for in-Water Testing of Marine Hydrokinetic Energy Devices

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***Abstract*- The ocean-energy industry is still in its infancy and device developers have provided their own equipment and procedures for testing. Currently, no testing standards exist for ocean energy devices in the United States. Furthermore, as prototype devices move from the test tank to in-water testing, the logistical challenges and costs grow. Development of instrumentation packages that can be moved from device to device is one means of reducing testing costs and providing data to the industry as a whole. As a first step, the U.S. National Renewable Energy Laboratory (NREL) is developing instrumentation packages that will provide common measurements across various ocean energy devices. Considerations in choosing an instrumentation controller are summarized in this paper using experiences from the oceanographic and wind industry. Some of the NREL National Wind Technology Center's wind turbine certification tests are suggested as examples of possible tests for MHK devices. Next, challenges that must be addressed in the development of the ocean instrumentation controller are outlined. For example, the instrument package must be adaptable to fit a large array of devices but still conduct common measurements. Finally, data file format and long term database storage options are outlined. NREL welcomes input from the industry regarding its measurement needs.**

I. Introduction

This paper is written to initiate ideas and questions rather than to present an already designed system. The scope of the paper has been limited to instrumentation and measurement controllers, data handling, and data storage. Reporting on test format, analysis of results, and individual sensors and instruments is out of the scope of this paper. An excellent source for a description of an overall testing project is found on The European Marine Energy Centre (EMEC) website [1].

Benefit to marine hydrokinetic device developers

Part of the development path for marine hydrokinetic (MHK) device developers is to build prototype devices to validate designs and find areas in need of improvement. This allows developers to test various subassemblies as a complete system and to demonstrate the feasibility of their design. Prototype testing usually progresses from small scale testing to larger scale and finally full scale. There is a need to measure device performance characteristics and dynamics at each of these scales. The National Renewable Energy Laboratory (NREL) has an interest in helping facilitate this testing so that MHK technology may develop at a more accelerated rate than would happen in the private sector alone.

Why should device developers want help with MHK device testing?

Often MHK devices have their own supervisory control and data acquisition systems (SCADA). Why should developers welcome external involvement in measuring device performance parameters? First, there are some fundamental differences in the purpose of measurements taken for an onboard control system or SCADA system versus a test and measurement system. The testing instrumentation system has a goal of accurately characterizing the MHK device as opposed to controlling the MHK device. A design requirement of the NREL testing instrumentation system is that it will be deployed as a common set of measurements that can be taken across the spectrum of MHK devices. The idea is that the testing results can be used as a benchmark of performance between devices. NREL has experience in processing test data and presenting it in a format that does not release sensitive proprietary data, while still allowing devices to be compared.

There are other benefits of working with NREL for performance testing. Test and measurement systems are expensive to build, deploy, and maintain. This is especially true in the marine environment where the specialized hardware needed can add many times the expense of land based testing. Testing may be unnecessarily burdensome to start-up companies. Using a supplied test and measurement system with support integrating the test system to the device is a large cost savings to these companies. The device developer's time, money, and effort can be better spent improving the MHK devices.

Certification Testing

Eventually third party certification of MHK devices will show that the device is commercially ready to attach to utility power grids. To collect the testing data needed for the certification process, a set of common measurements for a given test should be defined in the testing standards. The testing standards are in development and are an ongoing effort by the International Electrotechnical Commission (IEC) and others. The EMEC paper, "Performance Assessment For Wave Energy Conversion Systems in Open Sea Test Facilities" [1] contains a preliminary description of a performance test protocol for wave energy devices. NREL has developed instrumentation packages that perform the measurements needed for certification testing of wind turbines [4]. NREL intends to provide instrumentation packages for use in MHK device certification testing. By providing instrumentation that has been calibrated to American Association of Laboratory Accreditation A2LA standards, NREL can provide a valuable service to MHK developers.

Feedback and model validation

There is an ongoing significant effort to model MHK devices, and to estimate device parameters analytically. These models need empirical measurements as feedback to the modeling programs so that more accurate models can be developed. This helps to complete the design loop and will guide MHK device developers as they progress through the Department of Energy (DOE) Technology Readiness Levels (TRL) levels [6]. The measurement data for this effort should consist of a common measurement set and resolution so that data from multiple test deployments can be integrated.

Regional test centers

The Department of Energy and others are funding regional test centers for marine hydrokinetic testing devices. The plan is that the test locations will be pre-permitted test locations for MHK devices. The regional test centers will likely have cost-effective marine operations capabilities to help MHK developers since they are associated with university oceanography programs. The regional test centers will hopefully have a transportable testing component like those being planned for Oregon State University's Mobile Ocean Test Birth (MOTB). The centers can look to NREL to provide standardized testing equipment design, methods, and testing protocols for testing devices deployed at their locations. By providing consistent methodology and equipment to the regional test centers, a more standardized service will be provided to the industry.

II. TYPES OF DATA ACQUISITION SYSTEMS

Two basic types of data acquisition systems

In this paper, we present two contrasting data acquisition system architectures. These are meant as examples of existing technology and are not the only technology choices. The first is the wake up, sample, and sleep oceanographic instrument controllers like those built by the Monterey Bay Aquarium Research Institute (MBARI) [2], [3]. The second is the test systems in use at NREL's National Wind Technology Center (NWTC) that collects data from wind turbines and is a continuous data acquisition system based on the NI Compact DAC chassis [4]. Each of these systems has their own unique strengths and limitations.

Deterministic vs. nondeterministic measurement jitter

Now, a short digression to explain the difference between real-time operating systems (RTOS) and regular operating system, like in a PC, as used in a measurement system. A RTOS can resolve the time difference between when a measurement is received and the real-time clock. In essence, the RTOS measurement system can more precisely define when the measurement was taken. This deterministic measurement timing can be important for time critical measurements. In a standard preemptive multitasking operating system, there is ambiguity about when the data has been received and when the timestamp is attached to the data. If the processor becomes heavily loaded, there can be a timing error in the data's timestamp. This nondeterministic measurement jitter is usually small and can be made smaller by using a faster processor. If the processor is very busy, this error can be introduced as an error in the timestamp of the data record. With a RTOS, the measurement can be forced within at a particular time and the delay in the timestamp can be determined.

Strict testing requirements that would require the use of a RTOS in the test and measurement system are not anticipated for duration, power performance, and power quality testing of MHK devices. Test requirements requiring a high level of synchronization between analog channels would require an RTOS to take deterministic measurements. An example of this type of test may be one where multiple strain gauges and load cells are installed to measure the mechanical dynamics of a MHK device.

III. Oceanographic Instrumentation Controllers

An instrumentation controller, like those used in oceanographic observatory systems, collects data from many instruments and archives the data as a set of time stamped measurement records. The number of instruments that can be sampled simultaneously depends on the number of communication ports and the controller processor speed. The instruments connected to the controller are usually communicating with the controller via RS232 serial protocol. This is because the instruments are stand-alone instruments in their own waterproof housing. The instruments usually are designed for use as a stand-alone instrument or in an instrument controlled network. Two excellent examples of oceanographic instrument controllers are from the Monterey Bay Aquarium Research Institute. These are the SIAM [2] software running on their MOOS mooring controller, or PC104 hardware, and OASIS [3] software running on OASIS3 hardware. Timing measurement jitter from serial communication is not an issue in ocean observation systems that are long time-series measurement systems. The frame of reference for ocean-observing systems is over weeks, months, and years, thus measurement jitter on the order of milliseconds is not of concern.

Oceanographic instrument controllers are generally low power, robust systems, with a software library of instrument drivers available. Therefore, they can communicate with a large number of commercially available sensors. The instruments themselves are designed to measure items of interest to oceanographers. Available instrument drivers include those for wind, wave, and current measurement, which are of particular interest to MHK developers.

Low power requirements

The low power draw of oceanographic controllers makes them particularly useful in battery-powered deployments. The controllers have the ability to put themselves in a low-power sleep state in between sample periods and also turn on and off the instruments in between samples. This can make the batteries last a much longer time than on a system that must be permanently powered. If the measurement system must be deployed over a long period and battery powered, these systems may be the only option.

In ocean observation systems, there is less of a need to collect data from analog sensors. Consequently, support of analog sensors is not a high priority. Typically, there may be up to eight analog input channels available [3]. With PC104, the number of hardware analog channels is not a limitation but the controller software drivers may have poor performance or be nonexistent. This can be of concern to the MHK device developers because analog devices, like current transformers, potential transformers, resistive temperature devices, strain gauges, and torque sensors, are required for some tests. Oceanographic instrument controllers can collect these data from analog sensors, but they use additional hardware and software. Time sensitive requirements for these measurements may not be met.

Limited on-board storage for data

Oceanographic observatory systems usually have a telemetry link to shore to off load data. The maximum stored data size is that of the available removable storage, e.g., an SD card or a compact flash. If the available storage is filled before the data can be downloaded, the recording will either stop or start overwriting old data records. The available memory must be budgeted and managed for the expected size requirements. It is desirable to download the data off the test system to the safety of a permanent repository. The limited size of onboard memory is an issue for any instrumentation system.

Power management

Oceanographic buoy and observation system controllers can collect data from a multitude of instruments in the marine environment. The oceanographic controller has hardware and software to track the buoys available power and availability. The buoy's instruments can be run at a lower duty cycle if the available power decreases.

IV. Wind Turbine Field Testing

MHK devices are an emerging technology. A close analogy to MHK device testing is wind turbine testing. Some of the tidal turbines in development closely resemble underwater wind turbines. It is anticipated that most of the wind turbine tests conducted for certification will be adopted, with some modifications, for MHK device testing. NREL's website summarizes the wind turbine field-testing program [4]. In addition to field-testing, NREL also has dynamometer and blade testing facilities. NREL's testing program provides data that is used in wind turbine certification as well as third party validation for many aspects of wind turbine performance. NREL plans to make available to MHK device developers.

Accredited Testing

NREL has testing capabilities that are accredited by the American Association of Laboratory Accreditation (A2LA). Currently, NREL is one of only two facilities in the United States that are A2LA accredited. The suite of tests conducted on both small and large wind turbines includes acoustic noise emissions, duration, power performance, power quality, and safety and function. Each of the tests is briefly described below. Tests are performed to IEC standards and in compliance with NREL's A2LA-accredited Quality Assurance (QA) system. Duration, power performance, and safety and function test data are collected using a National Instruments-based data acquisition system and compiled through custom LabVIEW software.

Acoustic Noise Emissions

Acoustic noise emissions testing summarize typical noise levels emitted from the turbine at different wind speeds. Sound data are recorded (one tower height plus half a rotor diameter downwind from the tower base) and processed using Noiselab software. Noise testing is performed according to IEC Standard 61400-11.

Duration

Duration testing is performed to summarize the turbine's performance over long time periods. Test data are sorted monthly into time classes specified by the standard and submitted to the client in an informal report. Duration testing is performed according to IEC Standard 61400-2.

Power Performance

Power performance testing produces a power vs. wind speed graph to summarize the turbine's power generation performance at different wind speeds. This test is performed according to IEC Standard 61400-12-1, referencing Appendix H for small turbines. Data are analyzed for rejections based on wind direction, turbine status, and instrument readings, and then compiled through an Excel-based program to produce a power curve.

Power Quality

Power quality testing is performed according to IEC Standard 61400-21. This testing includes assessment of power, flicker, and harmonics levels for compliance with the standard. Turbines with a UL 1741-compliant inverter will not undergo power quality testing.

Safety and Function

Safety and function testing is performed to verify that the turbine displays its designed behavior as represented by the manufacturer. Features tested are drawn from the wind turbine documentation and may possibly include additional NREL-specified features. The testing is conducted in accordance with IEC Standard 61400-2.

Application to MHK Device Testing

All of the above tests can be applied to MHK device testing with some modifications. The LabVIEW test code can be modified to log additional instruments and at appropriate data rates. The LabVIEW software can run on many different platforms including embedded platforms.

V. Wind Turbine Test Data Acquisition Systems

The instrumentation systems used at NREL for wind turbine test systems are based on a National Instruments compact DAC chassis. The modules used can vary for a particular test listed in section IV. The data acquisition software runs on an accompanying PC and is written in National Instruments (NI) LabVIEW code. An advantage is the large number of off the shelf IO modules available to populate the instrumentation chassis. Reconfiguration of the test system is relatively quick depending on the reusability of the LabVIEW code. Software design practices that maximize the reusability of the code are strongly recommended for any test system software.

Analog sensor support

The strength of the NI Compact DAC-based system is the large number of input-output (IO) modules available. The system can support many types of sensors with high speed data rates to conduct sampling into the kilohertz range. A sampling rate in the kilohertz range is required for measuring harmonic components of voltage and current in the IEC power quality test standard. The LabVIEW programming language also has many useful tools to process the analog channels, display data, and store the data records.

Serial instrument support

National Instruments has RS232 serial IO modules available for Compact RIO, while the LabVIEW software drivers for the stand-alone oceanographic instruments may not exist and would have to be written. Writing new drivers in LabVIEW is not especially difficult for most instruments; however, the development time can be time consuming. Oceanographic instrument controllers have much more software support for serial networked instrumentation than do the National Instruments controllers.

Power Hungry

Wind turbine test instrumentation is connected to a permanent power source. There are several issues with trying to use a system designed for wind turbine test systems and apply them directly to MHK device testing. First and foremost, it is not practical to use a PC mounted on an offshore buoy to run the test code. It is not advisable to operate a PC as a data acquisition system on a buoy offshore or in an enclosure on the sea floor. There are several reasons why a PC is not advisable on an offshore buoy or subsea deployment; a PC uses more power than is necessary, it is not designed for harsh environments, its physically large size compared to other controllers, and it requires hands-on intervention periodically. There are many industrial PCs available with a form factor that may be acceptable; however, the power required to run the industrial PC may rule out its use in a battery-powered MHK device test. For at-sea deployments, a dedicated controller running only the test system code is preferable. It is possible to port the NREL National Wind Technology Center's LabVIEW wind turbine testing code over to a dedicated controller from National Instruments. The Compact RIO and Single-board RIO both run LabVIEW code from a FPGA with real-time OS to create a dedicated data-acquisition system. There are a large number of IO modules available for Compact RIO systems. The Compact RIO has the ability to programmatically go into low power sleep, like MBARI's instrument controllers, saving battery life.

High sample rate

One of the strongest points of the Compact DAC and Compact RIO systems is their ability to sample and store data at a very high sample rate. This is critical in applications when spectral analysis is being performed. NREL's IEC Power Quality system samples voltage and current at 25 kHz for 10 minutes during the test observation cycle. The power quality transient test sample rate is 5 kHz. The power quality measurement system uses National instruments Compact DAC. This is in contrast to the performance of MBARI's SIAM software running on a PC104 computer; it runs at around 4Hz maximum sample rate. This limitation is due to the SIAM software limitations while the PC104 data acquisition boards can run quite fast.

Deterministic measurement capability

If higher than standard measurement precision is required for a particular test, this can be accomplished using a NI Compact RIO that runs on the VxWorks RTOS. Having the additional precision available is a good goal as long as the cost and complexity of the system is not substantially increased. The RTOS in the Compact RIO can add some complexity to the software coding required. If special features of the Compact RIO, like the lower power sleep mode, are used, the programming drops lower down into the FPGA level.

VI. Integration to MHK Device

By necessity, each test instrumentation installation will be customized to some extent for each deployment. Each test system deployment is an integration effort that has its own specific requirements and a schedule that must be met for the test. There are some commonalities between testing any MHK system. All MHK device performance could be reduced to measuring the resource input power and device output power. However, there typically are many additional items to be measured, in addition to basic performance. When developing the test system, the initial hardware and software should be chosen such that components of the system can be used from deployment to deployment, reducing the reconfiguration effort whenever possible. As part of the design process, when common items are measured this should be done in a standardized fashion so that data across tests and devices can be compared, when applicable. Measurement best practices will eventually make it in to IEC testing standards and standards of other bodies.

Lists of questions that must be answered in order to successfully integrate the test instrumentation to the device are outlined below:

Space Requirements

How much space is available to mount test instrumentation controller chassis? How much space is available to mount individual sensors?

Form Factor

What form factors are available for a particular type of instrument controller? What effect does the form factor choice effect the available IO modules? Which IO modules are sufficient for the measurements required? How does the controller form factor impact the controller housing and available connectors that will fit the controller housing?

Test Instrumentation Power Requirements

Will the test instrumentation system provide its own power or can the power be provided by the test center or device under test itself? In the case of battery power, will the batteries be primary (single use) batteries or secondary (rechargeable) batteries? In the case of secondary batteries, how will they be recharged? Will the instruments themselves have on-board batteries or will the instrumentation controller provide the power?

Data/Telemetry Requirements

On board logging of measurements will be required. This is to provide the flexibility of deploying the test system in either a standalone or remotely communicated network topography. The amount of data that must be stored locally depends of the measurement frequency, data format (ASCII or binary), and the measurement type. Ideally, the data would be off loaded to a repository away from the device under test on a regular basis and the data would be available for analysis while the test is still ongoing. It is recommended that a radio modem be used to collect the data on a pseudo real-time basis. If something were to go wrong on the test system, or the device under test, there is a chance that accumulated data could be lost. This data could contain the information needed to reconstruct the source of the failure. Data could be downloaded in either an automated manner or by manual log in and download. During the longer deployment periods, an automated download approach would be favorable.

VII. DATA STORAGE AND PROCESSING

Data Files

The testing data files initially reside in the testing instrument controller. This raw data measurement file can be stored as ASCII text, a binary format, or a special measurement format like a Technical Data Management Streaming (TDMS) file format. The TDMS format has the benefit of having metadata associated with the measurement as part of the measurement file itself. Other systems like the MBARI SIAM system also keep the metadata association with the raw measurement. Much of the wind turbine testing data at the NWTC is stored in ASCII text, with the rest stored as TDMS format. It is recommended that the data storage format be one with the metadata stored with the raw measurements. This allows the information to be more usefully stored in a relational database.

Once the data files have been transferred to a central storage location, they should first be stored within a directory structure that allows the data files to be recovered by an operator or test engineer. After the data files have been archived, it is recommended that the data should be processed into a relational database for use in all analysis and reporting. Without a database, separate data file storage will eventually become cumbersome, thus leading to a large amount of administrative time. Human in-the-loop data file administration can lead to problems due to personnel attrition. Finally, when the files are stored separately, comparing data across tests can be a time consuming process depending on the analysis tools available.

Database

As mentioned previously, data records should uploaded into a relational database for long term storage. The advantages to having data stored in a database are many. Some of the highlighted reasons for storing data in a relational database include analysis across multiple measurements, analysis across multiple tests, storing metadata with measurements, customizing data security for different users, and providing high reliability storage.

The data records can be manually uploaded into the database or uploaded through an automated upload script. Automatic uploading and archival of data records is done at MBARI with their SIAM controller software and shore side database system (SSDS) [5] databases. In other instrumentation systems, data can be automatically uploaded into an SSDS database as well.

VIII. SUMMARY

NREL's MHK instrumentation package will be valuable to the industry by providing normalized testing data that leads to certification testing and eventually device accreditation. The choice of an instrumentation system depends on many factors outlined in this paper. A system designed with the goal of maximum flexibility will allow more of the system components to be used across tests of different MHK devices. Keep in mind that every test is unique and a test system for a particular test should be designed and assembled months in advance of a deployment date for smooth integration of the test system with the deployment. A set of common instrumentation hardware and software components can be applied to many different types of devices and particular tests. Over riding requirements for the test system are the time granularity of a particular measurement, the total time of test system deployment, the data sensors being deployed, and the power available to the instrumentation system. Some of the design requirements may be contradictory and tradeoffs may be necessary. The data file format should be one that allows the data to be ingested by a relational database for permanent storage and data analysis.

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