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Monitoring Ocean Turbines: a Reliability Assessment

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Abstract

Predictive maintenance of ocean turbines requires ongoing machine condition monitoring (MCM). As part of a reactive system, each piece and type of equipment exhibits both cyclic and transient behaviors, some of which may indicate faults that presage failures. This paper identifies a number of factors that impact reliability and safety of oceanbourne turbines. Fouling, salinity, and inaccessibility of equipment are but a few such factors that set this MCM problem apart from those encountered by wind turbines, hydroelectric plants, or ship hulls and propellers.

Keywords: ocean turbines, machine condition monitoring, power systems, reliability engineering, bio-fouling.

I. Introduction

Ocean and marine technology has greatly evolved over the past two decades. Manned and unmanned surface and undersea robots are routinely used, new energy harnessing technologies are emerging, and oil and fishing industries are using ever more sophisticated systems from high-resolution sonar to new materials. Complexity of ocean systems have been outpacing the technology to maintain and monitor them. Equipment reliability is essential to safety and mission critical at-sea operations. Breakdown maintenance (run-to-failure) cannot be applied to most ocean systems nor to a fleet of assets, as equipment breakdown may result in a catastrophic loss. Scheduled maintenance must be carefully planned, due to high cost of retrieving submerged equipment like ocean turbines.

This paper examines risk factors associated with deployment of a proposed fleet of turbines that harness the energy from the Gulfstream located about forty miles off the East coast of Florida. Key to this deployment is technology designed to monitor and optimize the performance of these and other complex ocean-related systems. This technology is finding its first application to a 20-kW turbine prototype [6] at the Center for Ocean Energy and Technology (COET) [7] at Florida Atlantic University [1]. Figure 1 shows the turbine and its moorings. This figure denotes (a) Northbound direction of the ocean current as seen from shore, (b) the monitoring and control buoy, (c) the barge used for passive orientation of the system, (d) a tether to the ocean floor, and (e) a *nacelle* that includes the turbine and connecting structures. Hence, the turbine is housed in a bouyancy controlled vessel tethered to a barge, with electrical and communication cabling to a bouy, and anchored to the seafloor via a towline.

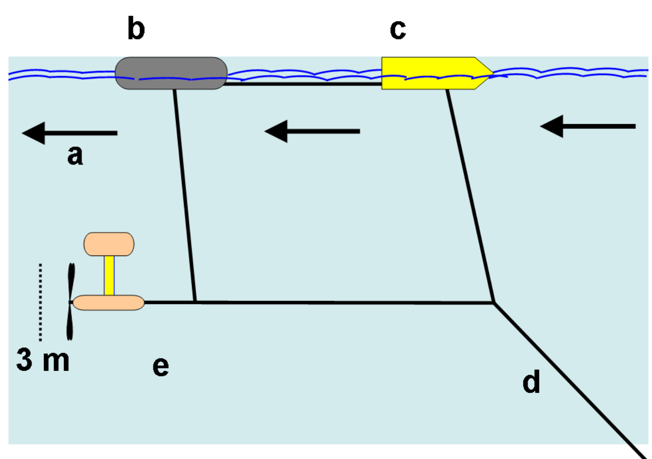

Fig. 1. Moorings for an ocean turbine

Figure 2 gives a closeup look at the turbine. A three-blade propeller (a), is connected to pressurized enclosure or nacelle (b). The nacelle contains an asynchronous electric motor/generator connected by a shaft supported by bearings and thence connected to a gear reduction box. Pitch, yaw, and roll of the nacelle are partially controlled by pressure buoy (c). Tubine blades occupy the most downstream portion of this design, where the nacelle and its blades are passively pulled by the gulfstream current. In the initial design, blade rotation is initiated by applying electric power at low RPM to the electric motor until the external water flow from the gulfstream produces a continuous and sustained rotation of the blades.

Its safety system operates independently from its moni-

[1]http://coet.fau.edu/

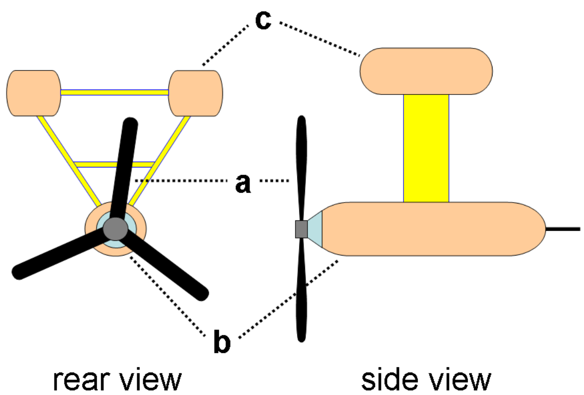

Fig. 2. Nacelle and adjoining structures

toring system and can halt turbine operation automatically in the event of a number of top-level faults. A non-exhaustive list includes signs of overheating, dynamic instability, leak, excessive voltage and current across the power plant, cable failure or dramatic change in propeller angular velocity (i.e., sudden stop). This safety system enables an external operator to properly shutdown the power plant.

The machine condition monitoring (MCM) system records and processes a series of measurements, producing a timed data stream for real time health assessment, prognostics, and advisory generation. Some of these measurments include mechanical vibration, propeller angular velocity, heat, cable tension, voltage and current of the power plant, lubricant quality, and video imaging. Some of the sensors are shared between the safety system and the MCM system. Due to its steep downside risk, the safety system samples data at a substantially higher rate than the one for MCM.

Both safety and MCM systems are distributed between submerged turbine and topside pontoon. Initially the user control and display is located on the pontoon, however, this functionality will eventually be migrated onto shore. The safety system uses lower latency serial communications to relay the safety information. The machine monitoring unit uses Ethernet due to its higher bandwidth. Data is relayed between turbine and pontoon via fiber-optic cables that can support a large number of sensors. Since this design presents a single point of failure, future designs might involve redundant channels implemented perhaps by acoustic modems to transmit safety-related signals. The wetside portion of the safety and MCM system is packaged as a self-contained unit approximating one cubic foot in volume. Initially at the topside, a user panel indicates the safety status through simple visual LED-type display and contains a switch for emergency shutdown. This functionality will be migrated to a shore-side control center, with the topside component remaining unmanned during routine operation. The topside portion is centralized to a single PC unit, collecting all the information on a single hard drive and displaying the health diagnostic and prognostic results using a single display. Future generations will add in spatial redundancy for these computing and networking resources.

1	fouling of blades and other mechanical components
2	impact on marine life including species affected
3	salinity that causes corrosion of network cabling
4	underwater turbulence affecting turbine operation
5	high cost to access equipment for servicing
6	equipment heterogeneity
7	presence/absence of technological maturity
8	eventual impact on global climate

TABLE I. Reliability concerns

The rest of the paper is organized as follows: Section II elaborates on reliability concerns that are unique to this application. Section III surveys related work. Finally, Section IV provides a summary and description of future work.

II. Reliability Concerns

Concerns that an MCM application can address include seasonally changing water currents, surface conditions that range from calm to rough, turbidity due to biological activity and suspended debris, and corrosion due to salinity. Other concerns that cannot be addressed by an MCM include distance from medical facilities in the event of an at-sea mishap, travel time required to the site, and cost of retrieving each turbine for servicing. These concerns set this MCM problem apart from ones involving wind turbines, hydroelectric plants, or ship hulls and propellers.

Table 1 lists broad classes of reliability concerns from specific to general, the top ranked of which are specific to ocean-bourne turbines. Somewhat less specific concerns follow and pertain to ocean-bourne systems in general. Finally, the most general concerns pertain to any human-made system.

Fouling of mechanisms is directly proportional to turbidity, which itself is inversely proportional to depth of submersion. Turbid waters can contain human-made debris, gelatanous species like jellyfish, and sessile organisms like barnacles and welks. For bio-fouling, factors in addition to depth include water temperature and time of year, which also influences velocity of water flow. COET is currently assessing these rates of fouling at their deployment location, with the development of a turbidity model left for future work. The presence of human-made structures (i.e., ocean turbines) and suspended debris (i.e., plastic bags) provide an ecological niche that attracts these and other fouling organisms. Known as *flocculation*, this process attracts marine life at successively higher levels of the food web, eventually including turtles and cetacean mammals. Flocculation both accellerates turbine failure and may ultimately expose threatened species to increased concentrations of floating plastic debris. Additionally, hazards associated with machinery rotating at less than one revolution per second cannot be overlooked. Assessments of these environmental impacts is left for future work.

Salinity can corrode all human-made structures with network cabling presenting a single point of failure. Corrosion of cabling disrupts identification of machine status. Backup/redundant communication channels using acoustic signaling has low bandwidth and high propagation delays [1], which limits their usefulness to short safety-critical status/shutdown signals. This communication problem for ocean turbines is a subproblem of that for autonomous underwater vehicles (AUV). As such, ocean turbines can assume three things that AUV's can't: (i) centralized topside master, (ii) tethering that simplifies routing and acousic relay of data, and (iii) ability to detect degree of bio-fouling of network cabling by percussing the tether to measure degree of dampened wave forms.

Underwater turbulence places stress on propellers and connecting structures and is inversely proportional to depth of submersion. Since January of 2009, COET had submerged acoustic Doppler current profilers (ADCP) at the deployment site to measure curents and turbulence at a variety of depths of submersion. Analysis of this data is left for future work. Whereas both turbidity and turbulence decrease with increased depth, accessibility cost and bathymetric pressure increase with depth, suggesting an internal optimum for depth of submersion. To minimize fabrication cost and pressure on seals, the initial deployment depth for the 20-kW prototype has been ten meters. Further turbidity and turbulence analysis along with design improvements for a next generation turbine may make greater deployment depths feasible.

The remaining reliability concerns are not specific to ocean turbines, nor even rotating machinery. Since ocean turbines are a relatively new engineering application, COET anticipates creating more generations of turbine prototypes. Each generation will not only produce more electricity, but also will ideally require a simpler design. What constitutes simplicity is not always clear. For example, the first generation 20-kW turbine uses a fixed pitch propeller, which requires an electric motor to initiate rotation to its operating speed of between 40 and 55 revolutions per minute. A variable pitch propeller will not require such a motor. However, varying propeller pitch could require more control logic, while exposing more moving parts to the harsh and turbid ocean environment. Each generation turbine would require modifications to the MCM, with some redefinition of equipment health indicators and failure modes.

III. Related Work

To date, few scientific papers concern reliable ocean turbine design. This is surprising considering the ocean's immense potential as a source of autonomous electric power generation. Reliability issues that set ocean turbines apart from other power generation systems, stem from the harsh yet fragile ocean environment in which they operate. Here we survey related literatures concerning its potential, its environment, MCM, and wind turbines.

a) Potential:: The potential for generating energy from ocean currents, including benefits and promising technologies were discussed in [14]. As early as the late 1970's the Coriolus Program [11] proposed construction of an array of large ducted catenary turbines moored about 30 km east of Miami. They provided early estimates of power available and listed environmental issues that needed to be addressed. They cited earlier studies that concluded, based on simulating the hydroelastic behavior of submerged components, that rotors will be free of adverse vibrations. Neither an ocean-deployed prototype nor any use of an MCM system was subsequently reported for that project. From this we surmise that reliability problems due to impact by the environment may have been overlooked.

b) Environment:: Fouling of submerged components by gelatinous zooplankton and sessile organisms has been widely studied in conjunction with ship's propellers and hulls. The impact on biota of increasingly prevalent human-made debris, mostly plastics, was assessed in one meta-study for the Caribbean basin [5]. The following paragraphs discuss the impact of fouling on submerged sensors and structures.

Sensors should be the last submerged components to be fouled by marine organisms. In the UCSD Spray Project [2], sensors mounted on their AUV stopped functioning after three to four weeks of deployment in the highly productive waters of the Monterey Canyon [21]. Although turbidity of Gulf Stream waters is substantially lower, achieving the reliability goal of a one-year troublefree deployment requires an array of on-board mitigation techniques. One such technique is to induce mechanical surface vibrations using piezopolymer transducers to prevent the adhesion of fouling species on immersed structures, particularly glass components like sensors and lenses [10].

Submerged structures, particularly rotating members, should be as free as possible from bio-fouling. Due to high cost per surface unit of such piezopolymers, coatings have been considered for rotating and structural members. Use of methyl caproate possibly combined with zinc pyrithione in a controlled depletion paint, has been shown to retard

[2] http://spray.ucsd.edu/

fouling by marine bacteria and algae [17]. Effectiveness of this solution in retarding flocculation will require more empirical study.

c) Machine Condition Monitoring:: Sensor technologies and inexpensive microprocessors birthed a vast literature on MCM. ISO Standard 13374 promulgates a six-layer architecture spanning Data Acquistion up through the Advisory Generation layers. Our brief survey follows this architecture, focusing on three aspects: (i) physical layer issues involving vibration, (ii) interface layer issues like data or sensor fusion, and (iii) logical layer issues involving remote monitoring and control of turbine farms.

On the physical layer, ISO Standard 13373 promulgates use of well-accepted practices for acquiring and evaluating vibration measurements over extended periods of time, emphasizing changes in vibration behavior rather than any particular behavior taken in isolation. This standard recommends procedures for processing and presenting vibration data and analyzing vibration signatures, particularly for rotating machinery [3], [4]. Expert systems (i.e., [8], [22]) have been proposed for vibration analysis for fault detection, where [22] applies adaptive order-tracking techniques to rotating machinery.

Middle or interface layer issues like data or sensor fusion has been studied for rotating machinery using machine learning techniques. Collecting signals that may indicate rotational imbalance vibration from an array of sensors, [12] extracts characteristic features of each vibration signal using an auto-regressive model, then implements data fusion with a cascade-correlation neural network.

For fault diagnosis of induction motors [15], signals emanating from multiple sensors are preprocessed and then put through a descrete wavelet transform for decomposition into different frequency ranges of products, followed by a feature extraction step. Finally, an ensemble of two decision-level fusion stategies are employed, including a form of Bayesian belief fusion and a fusion technique involving multiple agents. In this machine learning technique, fault features are classified using several classifiers with generated decisions in turn fused using a specific fusion algorithm.

Field balancing of rotors was addressed in [13] to reduce turbine vibration in power plants. Using a unidirectional sensor mounted on one bearing section does not capture complex spatial motions. Instead, the authors propose a field balancing technique involving multiple sensors situated at various bearing sections along with a data fusion technique. They applied a holospectral principle and a genetic algorithm to simulate and minimize rotor vibration, empirically validating results by field balancing several 300 MW turbo-generator units.

Remote monitoring and control of equipment health, specifically the role of information and communication technologies, was surveyed in [2]. The authors identified emergent roles of web and agent technologies for remote MCM and control, and traced their origins to efforts in distributed artificial intelligence. Their survey was organized in terms of the OSA-CBM (Open System Architecture Condition-Based Maintenance) framework [3], an implementation of ISO 13374. They conclude that limited consistent and systematic efforts have been made, in an isolated manner, to apply web service and agent techniques to MCM.

A case study in remote monitoring and diagnosis of a electro-mechanical system was presented in [19]. Of interest, is their development of a virtual (software) instrument using LabView. This may provide an approach to generating output from the Data Manipulation Layer up to the higher levels of the OSA-CBM (ISO 13374) framework. Messages from the top layers, particularly the Advisory Generation layer, can be implemented as a remote monitoring and control center using web services standards. Unfortunately, such implementations may involve many middleware layers that will impede timeliness, posing steep downside risks for safety-critical systems. Addressing this problem, [18] suggests an architecture for predictable and interactive control, with a case study involving remote laboratory experiments.

d) Wind Turbines:: Sharing many commonalities, experience from the wind energy sector can be applied to ocean turbines. IEC Standard 61400-25 stipulates how wind power plants should be integrated into the power grid to assure power system stability. A paper describes how this standard seeks to promulgate vendor-neutral messaging protocols [16].

Other standards like IEC 61850 and IEC 61499 specify automation of distributed power systems. Based on these standards, [9] proposes a means of combining functionality of IEC 61850-compliant devices with IEC 61499-compliant ”glue logic” via the communication services of IEC 61850-7-2. The result is the ability to customize control automation logic, particularly important for developing power generation systems. IEC 61850-compliant devices are abstractions of system components. On its bottom-layer, each (virtual) device corresponds to the set of all sensors responsible for a given portion of the turbine. For rotating machinery, a bearing assembly may be represented as several virtual devices, each located along the circumference of the assembly. The state of each virtual device is the collection of fused calibrated and de-noised signals emanating from its set of sensors.

Like wind turbines, ocean turbines may require optimizing orientation to maximize laminar flow over their blades, reducing vibration and improving reliability. One proposal [20] describes a smart sensor that is insensitive

[3] http://www.mimosa.org/downloads/43/specifications/index.aspx

to turbulent air flux, enabling measurment of incident wind direction and energetic transformation efficiency. This recently patented sensor extracts suitable information from the structural deformation of blade members, where deformation is a function of incident wind direction, velocity and vibration modes. Adapting this sensor to water will pose additional technological challenges, which we leave for future work.

IV. Summary and Future Work

This paper examines risk factors associated with deployment of a proposed fleet of turbines that harness the hydrokinetic energy of ocean currents. We proposed a 20-kW turbine prototype and identified a number of factors that impact its reliability and safety. Specific reliability concerns involve fouling, salinity, and inaccessibility of equipment.

Future generations of this design will add in spatial redundancy for computing and networking resources. This includes possibly redundant communication channels for safety-related signals, and the migration of the MCM application from topside onto shore. Mitigation strategies we have found most effective in the prevention of bio-fouling of turbine blades and in the preservation of the marine environment will be subject of further work. More specific descriptions of our MCM implementation is also left for future work.

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