Failure Modes and Effects Analysis of an Aquaculture Feeding Barge Equipped with Wind Turbines

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This study focuses on the risk analysis of technical aspects of a feeding barge system equipped with wind turbines, to partially/in-full substitute the diesel generators currently utilised. The breakdown of subsystems and their components are presented. The Failure Modes and Effects Analysis (FMEA) approach has been used to identify the failure modes of each component and the Risk Priority Numbers (RPN) are presented to benchmark risks according to their criticality. 40 failure modes have been identified. Most of the subsystems in the feeding barge platform (apart from the electricity system, which have relative high RPN values) and mooring system show low risks, while the nacelle in wind turbine presents some critical risks.

Keywords: offshore wind technology, multi-purpose platform, aquaculture, failure modes and effects analysis, renewable energy, risk identification.

1. Introduction

Since 1970, the aquaculture industry has been expanding rapidly with an average growth rate of 8.8% per annum and it is set to expand further in the next decades (Arthur et al., 2009). Currently, the power supplied to aquaculture facilities that cannot be connected to the local electrical grid rely on diesel generators (Recalde et al., 2019). However, diesel-generated electricity may be very expensive, and aquaculture operators are more and more sensible toward sustainability of their processes. Inspired by the Multi-Purpose System concept (Muliawan et al., 2013, Casale et al., 2012, Christensen et al., 2015, Quevedo et al., 2013, H2Ocean, 2018), combining aquaculture and renewable energy, the feeding barge has been proposed to act as a support structure for wind turbines, coupled with an energy storage system to substantially displace or eliminate the need of diesel generators (Abhinav et al., 2019).

As the Multi-Purpose System is a relatively new concept, risks arise from the combination of multiple activities and technologies, and this topic has been studied to a limited extent in literature (Buck and Langan, 2017). Currently, most of the research related to risk analysis focuses on single onshore and fixed OWTs, instead of the whole hybrid system. By applying the failure rate data from onshore wind turbines with related marine environment databases, Delorm et al. (2016) analyzed five horizontal-axis OWTs reliability and found that the blades, generator and the converters needs the most effort in maintenance. Proskovics (2017) pointed out that 90% of insurance claims in offshore wind are from the cable damages. Carroll et al. (2016) have summarized the failure rates of 350 OWTs throughout Europe and a higher failure rate of the generators and converters were found for onshore wind turbines than offshore. Leimeister and Kolios (2018) have reviewed and classified reliability-based methods, both qualitative and quantitative for risk analysis, applied in offshore wind industry, where the details and differences between each of the methods are given, such as the Fault Tree Analysis (FTA) and the FMEA.

Proceedings of the 30th European Safety and Reliability Conference and
the 15th Probabilistic Safety Assessment and Management Conference.
Edited by Piero Baraldi, Francesco Di Maio and Enrico Zio

ISBN: 981-973-0000-00-0 :: doi: 10.3850/981-973-0000-00-0 esrel2020psam15-paper

Kang et al. (2019) have applied the FTA on semi-submersible floating OWTs. They found that the generator failure was mainly caused by leakage, and the top three failures are in the support platform, pitch and hydraulic system. Zhang et al. (2016) also used the FTA for floating OWTs. The failure data was employed from offshore structures for the analysis of the floating wind turbine's platform and mooring system and the broken line was found to be the primary failure mode.

Apart from the FTA, the FMEA, which is a method for evaluating the potential failure modes and their effects of an item or process (BS EN IEC 60812 2018), is also an appropriate semi-quantitative approach for the analysis of risks of wind turbine systems. Luengo and Kolios (2015) have presented a detailed failure mode identification for OWTs during their designed service life. Arabian-Hoseynabadi et al. (2010) have applied the FMEA on a 2 MW wind turbine with two different generators, where the ten highest ranking failure modes are presented. Kahrobaee and Asgarpoor (2011) have applied a risk-based FMEA on a 3 MW wind turbine, where for the detailed components in the wind turbine system, the FMEA process and the Risk Priority Number (RPN) are presented. The FMEA uses the RPN to identify the most critical failure modes (Kolios et al., 2017). Shafiee and Dinmohammadi (2014) have used the FMEA on both onshore and OWTs. They suggested that the FMEA is suitable for use at the design stage of a new wind turbine configuration. Kang et al. (2017) have modified the traditional FMEA and applied it on a floating OWT where high RPNs are found in the generator, floating platform, mooring system, and electronic components corresponding to a higher probability of failure than for structural components. Scheu et al. (2019) presented the most critical failure modes of the wind turbine systems from a total of 337 identified individual failure models based on more than 70% of the OWTs installed in Europe today.

This literature review highlights the high risks of failure in the wind turbine's electrical system and lack of detailed risk analyses on hybrid floating systems. The present work discusses the application of a FMEA approach focusing on technical risks performed specifically for a novel energy/feeding barge MPP, used for supplying power to an offshore aquaculture farm. The required data for the analysis of risks are collected from experts in aquaculture systems/OWTs, with more than 20 years of professional experience in the field (see acknowledgements), and also references from previous published studies, (Khan et al., 2005, Bharatbhai, 2015, Ozturk et al., 2018, Arabian-Hoseynabadi et al., 2010, Colli, 2015, Khan, 2005, Shafiee and Dinmohammadi, 2014, Basu, 2015, Tchakoua et al., 2014, Rastayesh et al., 2019, Das et al., 2011).

2. Risk management of an MPP

The reference MPP of this study consists of four wind turbines with a feeding barge platform, which can provide power for 8 to 10 fish cages (Abhinav et al., 2019). The four wind turbines can provide 70% of energy for the fish farm (Recalde et al., 2019). The feeding barge platform, used primarily to store and distribute the fish feed to the aquaculture cages and to monitor the fish growth, is here also used as support structure for the wind turbines. In this study, the risk analysis for the INNO-MPP will mainly focus on the technical aspects of the feeding barge system, which includes three subsystems: the feeding barge platform, mooring system and wind turbine, as shown in Fig. 1, where the blue rectangle represents the feeding barge platform; the navy triangle represents the mooring lines; the red circle is for the anchors; the green arrows represent the wind turbines, and the yellow L-shape symbolizes the feeding pipe. The FMEA will be applied to all the items within the black dashed line rectangle.

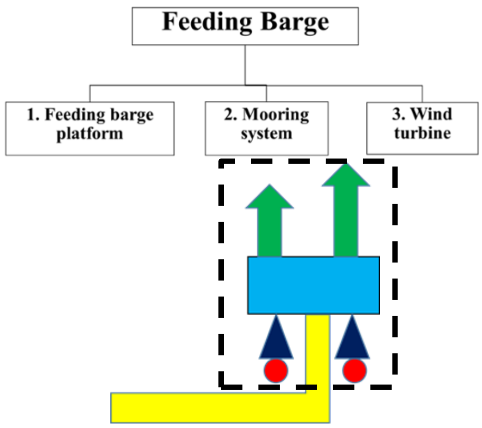

Fig. 1. The three subsystems in the feeding barge system

3. Risk policy

To conduct the FMEA, which focused on the risk analysis of the technical aspects of the feeding barge system, the subsystems and their components/sub-subsystems will need to be identified first. Section 4 gives the details of the subsystems. According to the adopted FMEA standard –BS EN IEC 60812 (2018), the steps below show the risk policy developed for this study:

- Step 1: identify failure modes;
- Step 2: identify failure causes;

- Step 3: estimate the likelihood of the occurrence of failure cause;
- Step 4: identify the failure effect;
- Step 5: determine the severity of the failure effect;
- Step 6: identify the control methods (to prevent the happening of failure);
- Step 7: score the detectability;
- Step 8: calculate the RPN
- Step 9: recommendation for risk control

The value of the RPN shows how critical each of the identified failure modes is, and is calculated as:

$$RPN = O*S*D \qquad (1)$$

where *O* represents the probability of occurrence, *S* represents how severe is the consequence of the failure mode, and *D* represents how easy it is to detect the failure mode. The criteria classification for the *O*/*S*/*D* adopts a ranking from 1 to 5 in this study, where '1' implies the 'most favourable' (low probability of *O*/low consequence of *S*/high probability of *D* prior to a failure occurring), and '5' implies the least favourable condition for each of the risk criteria.

4. Subsystem description

In the feeding barge system, the three subsystems contain 15 assemblies and 40 components in total. This section gives the detailed description of the subsystem and their components.

4.1 *Feeding Barge Platform*

The feeding barge's functions are: to accommodate the fish feeding system; to act as a floating support structure for the wind turbines; to accommodate the electricity storage and management system. Thus, it contains the following subsystems:

- Feeding system, which contains: tanks (to store fish feed); pumps (to transport the feed to the aquaculture cages); connections between barge and pipes (for delivering the fish feed)
- Ballast system, to control the stability of the barge platform, which contains: tanks (to store the ballast liquid, usually sea water); pumps (to adjust the amount of ballast liquid); valves (to control the ballast fluid flow direction in the ballast system)
- Bilge system, to dispose unwanted water in the platform.
- Electricity system, to manage the power for the feeding system and ballast system.

4.2 *The mooring system*

The mooring system has the function to restrain the horizontal displacements of the platform, and consists of the following elements: Anchor, Pulling rope, Bottom chain, Connection chain/anchor, Connection chain/mooring line, Mooring lines and Fairleads.

4.3 *The wind turbine*

The wind turbines capture wind energy and generate electricity for the whole system, and are composed of a tower, a nacelle and a rotor. In this study, the selected wind turbines (Aeolos-H20 and Polaris P1020) are direct drive wind turbines and have no pitch actuators (Recalde et al., 2019).

5. Data collection and analysis

Following the FMEA risk policy steps shown in Section 3, the potential failure modes, the associated failure effects and causes of failure, and the resulting RPN for each component in each subsystem, are identified and calculated. The information is collected from experts in offshore floating structures, aquaculture systems, and wind turbines.

Table 1 and Table 2 present the FMEA results of each component in the feeding system of the feeding barge platform. It shows that the components in the tanks and pumps generally present a lower risk profile, while the pipe connections between barge and the pipes experience higher RPN. This is due to the high probability of the detachment of the pipe connections between the barge and pipes, which will result in the feed dispersion and pipes flooding. In addition, as shown in Table 1, it is very hard to detect in advance. For the imperfect closure/accidental openings of the watertight doors for feed loading in the tanks, although it is easy to be detected and it is quite unlikely to happen, it could result to very severe consequences.

Table 1 RPN for potential failure modes of the feeding system components

Component ID	Subsystem	Component/Sub-component	Potential failure mode	*O*	*S*	*D*	*RPN*
1.1.1.1	Tanks	Watertight doors for feed loading	Imperfect closure/accidental openings	1	4	2	8
1.1.1.2	Tanks	Feed levels sensor	Wrong readings	1	2	3	6
1.1.2.1	Pumps	Blowers	Low air pressure delivered	2	3	1	6
1.1.2.2	Pumps	Air/water separator	Moist into air stream	1	1	1	1
1.1.2.3	Pumps	Air cooling system	Hot air stream, air pressure failure	1	1	1	1
1.1.2.4	Pumps	Rotary doser/auger	Clogging	3	2	3	18
1.1.2.5	Pumps	Dosing sensor	Wrong readings	1	2	3	6
1.1.2.6	Pumps	Electrical engine/reductor	Failure due excessive loads	1	2	1	2
1.1.2.7	Pumps	Selector valves	Failure	2	2	3	12
1.1.3.1	Connection between barge and pipes	Pipes connections	Detachment	3	3	4	36

Table 2 Potential effects and causes of failure for the feeding system components

Component ID	Potential effect(s) of failure	Potential cause(s) of failure
1.1.1.1	Water/moisture in feed, up to flooding	Fault on sealing
1.1.1.2	Wrong feed stocking, barge unbalance	Sensor failure
1.1.2.1	Feed clogging in air duct, up to cages	Fault on sealing, mechanical fault
1.1.2.2	Feed clogging in air duct, up to cages	Fault on automatic discard
1.1.2.3	Feed grease melting, pneumatic component clogging	Marine fouling on external cooling pipes/ accidental hurt/ fan failure
1.1.2.4	Wrong feed dosing	Moist feed, excessive dust in feed
1.1.2.5.	Wrong feed dosing	Moist feed, excessive dust in feed
1.1.2.6	Feed dosing impossible	Extraneous bodies in feed, failure in other components
1.1.2.7	Feed delivering to selected cages impossible	Moist/salt/dirt in actuators
1.1.3.1	Feed dispersion, pipes flooding	Harsh marine conditions

Table 3 and Table 4 show lower RPNs for sensors' failure (e.g. wrong readings), due to its low probability of occurrence and ease of detection, but the effects could be more severe as they will affect the balance/buoyancy of the feeding barge platform.

In the bilge system, as shown in Table 5 and Table 6 although the failure of the tank level sensor (ID: 1.3.1.1) and wrong readings of the inclinometer have low probability of occurrence and are easy to be detected, it can cause flooding in the floating platform, which is a very severe effect.

Table 7 and Table 8 present FMEA results for the electricity system in the feeding barge platform. The generator has a low probability of failure, but it is very hard to detect. The failure of the inverter appears to be a very critical risk, which leads to loss of energy output or reduced output. Another critical risk is the energy storage system, which show very high value of *S* and likelihood to occur in the two failure modes.

Table 3 RPN for potential failure modes of the ballast system components

Component ID	Subsystem	Component/Sub-component	Potential failure mode	*O*	*S*	*D*	*RPN*
1.2.1.1	Tanks	Tank level sensor	Wrong readings	1	3	1	3
1.2.1.2	Tanks	Inclinometer	Wrong readings	1	4	1	4
1.2.2.1	Pumps	Pump sensor	Wrong readings	1	3	1	3
1.2.3.1	Valve	Actuator sensor	Wrong readings	1	3	1	3

Table 4 potential effects/causes of failure for the ballast system components

Component ID	Potential effect(s) of failure	Potential cause(s) of failure
1.2.1.1	Unbalanced tank filling	Sensor failure
1.2.1.2	Barge unbalancing	Sensor failure
1.2.2.1	Wrong tank filling/empting	Sensor failure
1.2.3.1	Wrong tank filling/empting	Sensor failure

Table 5 RPN for potential failure modes of the bilge system components

Component ID	Subsystem	Component/Sub-component	Potential failure mode	*O*	*S*	*D*	*RPN*
1.3.1.1	Pumps	Tank level sensor	Wrong readings	1	4	1	3
1.3.2.1	Sensors	Inclinometer	Wrong readings	1	4	1	4

Table 6 potential effects/causes of failure for the bilge system components

Component ID	Potential effect(s) of failure	Potential cause(s) of failure
1.3.1.1	Wrong bilge empting/potential flooding	Sensor failure
1.3.2.1	Wrong bilge empting/potential flooding	Sensor failure

Table 7 RPN for potential failure modes of the electricity system components

Component ID	Subsystem	Component/Sub-component	Potential Failure mode	*O*	*S*	*D*	*RPN*
1.4.1	Electric system	Generator	Wear, break down	1	1	4	4
1.4.2	Electric system	Cables	Wear and tear	2	4	3	24
1.4.3[a]	Electric system	Energy storage system	Disfunction	2	5	2	20
1.4.3[b]	Electric system	Energy storage system	Improper function	3	4	2	24
1.4.4[a]	Electric system	Inverter	Fails to transfer	4	5	1	20
1.4.4[b]	Electric system	Inverter	Degraded output	4	4	3	48
1.4.5	Electric system	Protection system	Electrical overload and short circuit	3	4	2	24

Table 8 potential effects/causes of failure for the electricity system components

Component ID	Potential Effect(s) of Failure	Potential Cause(s) of Failure
1.4.1	No power transmitted	Improper lubrication
1.4.2	No energy output, safety	Faulty cabling, aging, extreme weather conditions
1.4.3[a]	No output, safety risk	Mechanical damage, open contacts, ageing, controller fault
1.4.3[b]	Performance deterioration, safety risk	Controller fault, poor contacts, corrosion, ageing, irregular maintenance
1.4.4[a]	No output	Contact damage, board problem, software failure
1.4.4[b]	Reduced output	MPPT unbalance, extreme weather conditions
1.4.5	System fails to absorb overload	High temperature, wear-out of insulation, faulty components

The probability of occurrence of the failures in the mooring system is very low, as shown in Table 9, but can lead to the loss of the whole system, and the failures of most of the underwater components, such as the anchors and connections between chain and anchor or mooring line, are somewhat hard to detect.

Compared to the feeding barge platform and the mooring system, the wind turbine shows higher RPN values. The most critical risks belong to the controller, as shown in Table 11 and Table 12, where the short circuit failure mode is likely to happen, and will stop the transfer of information to the control room. Another potential failure mode with a high RPN is the electrical overload and short circuit of the converter system (*ID: 3.2.4*), which would result in a failure to export the wind energy harvested to the (local) grid. The fatigue/fracture/erosion of the blades is also one of the critical risks, which will cause the blade to delaminate and fracture.

Table 9 RPN for potential failure modes of the mooring system components

Component ID	Subsystem	Component/Sub-component	Potential failure mode	*O*	*S*	*D*	*RPN*
2.1	Mooring system	Anchor	Displacement	1	5	4	20
2.2	Mooring system	Pulling rope	Breaking	1	2	2	4
2.3	Mooring system	Bottom chain	Breaking	1	5	3	15
2.4	Mooring system	Connection chain/anchor	Breaking	1	5	3	15
2.5	Mooring system	Connection chain/mooring line	Breaking	1	5	3	15
2.6	Mooring system	Mooring lines	Breaking	2	5	2	20
2.7	Mooring system	Fairleads	Breaking	1	5	1	5

Table 10 potential effects/causes of failure for the mooring system components

Component ID	Potential effect(s) of failure	Potential cause(s) of failure
2.1	Barge unmooring	Excessive loads
2.2	Wrong anchor tensioning	Wrong mooring installation
2.3	Barge unmooring	Excessive loads
2.4	Barge unmooring	Excessive loads
2.5	Barge unmooring	Excessive loads
2.6	Barge unmooring	Excessive loads
2.7	Barge unmooring	Excessive loads

Table 11 RPN for potential failure modes of wind turbine components

Component ID	Subsystem	Component/Sub-component	Potential failure mode	*O*	*S*	*D*	*RPN*
3.1	Tower	Tower	Corrosion, fatigue and fracture	1	5	3	15
3.2.1[a]	Nacelle	Yaw system	Seizure, corrosions on yaw bearings	3	1	5	15
3.2.1[b]	Nacelle	Yaw system	Electric motor failure	3	1	5	15
3.2.2	Nacelle	Cables	Wear and tear	2	4	1	8
3.2.3	Nacelle	Break system	Fatigue, failure	2	1	4	8
3.2.4	Nacelle	Converter system	Electrical overload and short circuit	3	5	3	45
3.2.5	Nacelle	Controller	Short circuit	3	4	4	48
3.2.6	Nacelle	Rotor shaft	Fatigue and fracture	1	1	3	3
3.3.1	Rotor	Blades	Fatigue/fracture/corrosion	3	4	3	36
3.3.2	Rotor	Hub	Fatigue and fracture	3	1	2	6

Table 12 potential effects/causes of failure for wind turbine components

Component ID	Potential effect(s) of failure	Potential cause(s) of failure
3.1	Loss of structural integrity and subsequent collapse	Weather effects and extreme conditions
3.2.1	Bearing failure due to excessive heat	Poor or incorrect lubrication
3.2.1	Turbine rotor gets stuck in a position and loses wind power	Motor component(s) failure
3.2.2	No energy output, safety	Faulty cabling, aging, extreme weather conditions
3.2.3	Rotor fails to stop at the right wind path	Wear or excessive pressure
3.2.4	Wind energy fails to be converted into usable energy	Electrical current surge. Low insulation levels cause electrical failure
3.2.5	Inability to transfer information to the control room	Moisture penetration or lightning strike
3.2.6	Cracks leading to failure. Misalignment results in excessive loading on shaft and bearing	Fatigue induced due to stress raiser such as improper grooves or welding defects, or misalignment
3.3.1	Blade delaminating and fracturing	High induced stress levels due to operation in high winds, cyclic loading or lightning strike
3.3.2	Fracture in the shell, rotor breaks, leading to wind turbine failure	High induced stress levels due to operation in high winds or lightning strike

6. Discussion

Regular inspection and maintenance can prevent most of the failure modes from happening, such as the wrong readings of the feed levels sensor, the clogging of rotary doser/auger, wrong readings of the dosing sensor, failure of selector valves, wrong readings of water level sensor in the bilge system. Installation of monitor alarm/gauge/sensor/inclinometer can also help to prevent the occurrence for some failure modes, such as defective feed system watertight doors, the failure of the blowers and the air cooling systems of the feeding system, the pump sensor and actuator sensor in the ballast system, etc. Visual inspection can help with the prevention of failures in the electric cables and energy storage system. In addition, automatic regulators integrated in the system, proper installation and regular inspection can also help to prevent the failure in the electrical system in both the feeding barge platform and the nacelle in the wind turbine, such as the inverter, protection system (*ID: 1.4.5*) and converter system.

To detect the causes of the failure modes, common methods can be employed, such as fault detection alarms for the sensors in the ballast system, or visual detection, such as the cables and energy storage system in the electricity system. Failures of the mooring system's components can be detected with divers and/or ROVs. For the failures in the blades or hub, the ultrasonic (Martinez-Luengo et al., 2016) and active thermography and visual inspection can be applied for the detection.

In order to qualify appropriate risk control methods, a systematic reliability-centered maintenance approach can be adopted.

7. Conclusion

In this study, an FMEA of an offshore aquaculture feeding barge equipped with wind turbines and an energy storage system has been performed, focusing on the technical risks, identifying and prioritising 40 failure modes. Each component has been analysed, identifying their potential failure mode(s), effect(s) and cause(s), quantifying the relative RPNs. Most of the components in the feeding barge platform are characterised by relatively low risks, apart from the electricity system and in particular the inverter, which has a very high RPN. The mooring system's components are designed to be reliable and are therefore characterised by a low probability of failure, but the effects of a failure would be severe. The nacelle system in the wind turbine shows more critical failure modes than the other systems, especially for the converter system and the controller. The blades of the rotor show high risks to fracture when experiencing extreme weather conditions. Current control methods in prevention/detection are briefly discussed.

Acknowledgement

This work is supported by the UK Engineering and Physical Sciences Research Council UK (EPSRC) and the Natural Environment Research Council UK (NERC), through grant EP/R007497/1 and EP/R007497/2, and the Natural Science Foundation of China (NSFC) through grant 51761135013. Special thanks to Dr Hong Yue, Dr Luis Recalde Camacho and Dr Giulio Brizzi (http://www.chlamys.it) for their valuable input in data collection.

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