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ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

Design Failure Mode Effect Analysis (FMEA) Report

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1.0	Final	27-Sep-2017	DFMECA procedure worked out in general; starting point for analysis of the whole tidal array	Jan Hofman	Hanno Spoelstra
1.1	Final	28-Sep-2017	Small lay-out changes to figures. Appendix I excluded as it contains Commercially Confidential information – replaced by an actual output from the analysis as an example.	Jan Hofman	Hanno Spoelstra
1.2	Final	Nov-2017	Transposed into template format	Neil Simpson	N/A

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1 Introduction

A Funding Grant was awarded from the European Union's Horizon 2020 research and innovation programme in January 2017 to demonstrate a grid-connected tidal energy array at a real-world tidal energy site, propelling tidal energy towards competing on a commercial basis with alternative renewable sources of energy generation – Enabling Future Arrays in Tidal (EnFAIT). This was in response to the call *LCE-15-2016: Scaling up in the ocean energy sector to arrays* to generate significant learning through demonstration of cost-effective tidal arrays.

This document is produced to set out the Design Failure Mode, Effects and Criticality Analysis (DFMECA) for a tidal array to ensure that potential turbine and array failure modes with their associated causes have been considered and addressed in the array design stage. It is also to be submitted to satisfy deliverable D9.2 of the EnFAIT project and to be made available for public dissemination.

This version of the document outlines the DFMECA process in general – as a methodical approach – which is applied to this project. It includes the documented output of the DFMECA for the shaft seals and bearing unit as a first example of future deliverables.

2 The Design FMECA process

2.1 Definition of a Design FMECA

Design FMECA[1] (DFMECA) is a methodical approach used for identifying all potential risks introduced in new or changed design of elements of the array.

- The DFMECA initially identifies design functions, failure modes and their effects on the operation of the array (based on previous, related experiences) with corresponding severity ranking / danger of the effect.
- Then, causes and their mechanisms of the failure mode are identified. High probability causes, indicated by the occurrence ranking, may drive action to prevent or reduce the cause's impact on the failure mode.
- The detection ranking highlights the ability of specific tests to confirm the failure mode / causes are eliminated.
- The DFMECA also tracks improvements through Risk Priority Number (RPN) reductions. By comparing the before and after RPN, a history of improvement and risk mitigation can be chronicled.

The emphasis in DFMECA is on failure prevention, leading to continuous improvement and increased asset reliability.

[1] For this project, it was opted to use the Failure Mode, Effects and Criticality Analysis (FMECA) methodology versus the related Failure Mode and Effects Analysis (FMEA) methodology. An FMEA analysis only identifies the effects of a failure, while the an FMECA analysis identifies the criticality of a failure. In the latter case, not only the effect of the failure, but also the likelihood of it occurring is identified. Thus, we have assured the first step in risk management (as per ISO 31000): the identification, assessment, and prioritization of risks associated with the technical failures of an asset. Risk management is an important process within the scope of Asset Management (as per ISO 55000), thus it is ensured this project uses international standards as appropriate and applicable to its scope.

2.2 DFMECA within the EnFAIT Project

The DMFEA Process described below is a methodology which needs customizing to be able to meet the specific requirements of the array.

Topics that need to be tailored and validated are:

- Main inputs and desired outputs of the array.
- Asset Configuration: Functional Decomposition and/or Product Breakdown Structure of the array.
- Occurrence rating table.
- Severity rating table.
- Detection rating table.

2.3 The DFMECA Process in general

Before starting the DFMECA Process the scope of the DFMECA must be determined. A boundary diagram as shown in figure 3 can be useful.

Going through the DFMECA process:

1. Functions

List the *functions* for each part or component; what is the purpose of this system, part or component, what is it expected to do? Name it preferably with a verb followed by a noun.

2. Failure modes

List all the *potential failure modes* – ways in which the system, subsystem or component could potentially fail to meet or deliver the intended function.

- In other words, what is the product NOT supposed to do.
- Describe these in physical or technical terms, not as a symptom noticeable to the customer.
- Assume that the part has been manufactured correctly.
- Focus on failures of the product, not the design process.
- There may be more than one failure mode for each function – they generally fall into one of four categories –
  i. No function;
  ii. Partial or degraded function;
  iii. Intermittent function;
  iv. Unintended function.

3. Failure effects

List the *effects* for each failure mode, in terms of what the customer or the business would notice or experience:

- There may be more than one effect for each failure mode.
- State the effects in terms of the specific system, subsystem or component being analysed.
- State clearly if the failure could impact safety or cause non-compliance to regulations.

4. Severity

Rank the *severity* of each effect:

- Identify any special characteristics. Special characteristics are elements which are of high importance to the customer or sponsor. A characteristic which affects safety or is related to legal or environmental compliance is normally referred to as a Critical Characteristic (CC). These will generally have a severity rating of 9 or 10.
- Other Significant Characteristics, which affect the form, fit or function of the product, are denoted by SC. A robustness study is useful for determining SCs.

These characteristics always take priority when assigning actions during a DFMECA, and Critical Characteristics take higher priority than Significant Characteristics.

Severity ranking table

Effect	Design criteria (Severity of effect on product; Customer effect)	Ranking	Effect	Process criteria (Severity of effect on process)
Hazardous without warning	Potential failure mode affects safe operation and/or involves non-compliance with government regulation without warning	10	Failure to meet safety and/or regulatory requirements	May endanger operator (machine or assembly) without warning
Hazardous with warning	Potential failure mode affects safe operation and/or involves non-compliance with government regulation with warning	9		May endanger operator (machine or assembly) with warning
Loss or degradation of primary function	Loss of primary function (inoperable, does not affect safe operation)	8	Major disruption	100% of the product may have to be scrapped. Line shutdown or stop
	Degradation of primary function (operable, but at reduced level of performance)	7	Significant disruption	A portion of the production run may have to be scrapped. Deviation from primary process including decreased line speed or added manpower
Loss or degradation of secondary function	Loss of secondary function (operable, but comfort convenience functions at reduced level of performance)	6	Moderate disruption	100% of the production may have to reworked offline before being accepted
	Degradation of secondary function (operable, but comfort convenience functions at reduced level of performance)	5		A portion of the production may have to reworked offline before being accepted
Annoyance	Appearance or audible noise, operable, item does not conform and noticed by most customers (> 75%)	4		100% of the production may have to reworked in station before it is processed
	Appearance or audible noise, operable, item does not conform and noticed by many customers (25 to 75%)	3		A portion of the production may have to reworked in station before it is processed
No effect	Appearance or audible noise, operable, item does not conform and noticed by discriminating customers (< 25%)	2	Minor disruption	Slight inconvenience to process, operation or operator
	No discernible effect	1	No effect	No discernible effect

Table 1: Severity ranking (note: this table is to be customized for this project)

5. Failure causes

Identify failure *causes* for failure modes.

A Parameter Diagram (P-diagram) can be useful to identify and categorise potential failure modes and causes (see figure 1):

- Each noise factor[2] from the P-diagram is a failure cause.

[2] Noise Factors are things that can influence the design but are not under the control of the engineer, such as environmental factors, customer usage, interfaces with other systems, degradation over time, piece-to-piece variation, among others.

- Assume that the manufacturing and assembly processes are perfect.
- Describe the cause in terms of something that could be corrected or controlled.
- Ensure descriptions are unambiguous.
- Try to ensure that the causes are described as failures of the part or component, not failures of individuals.

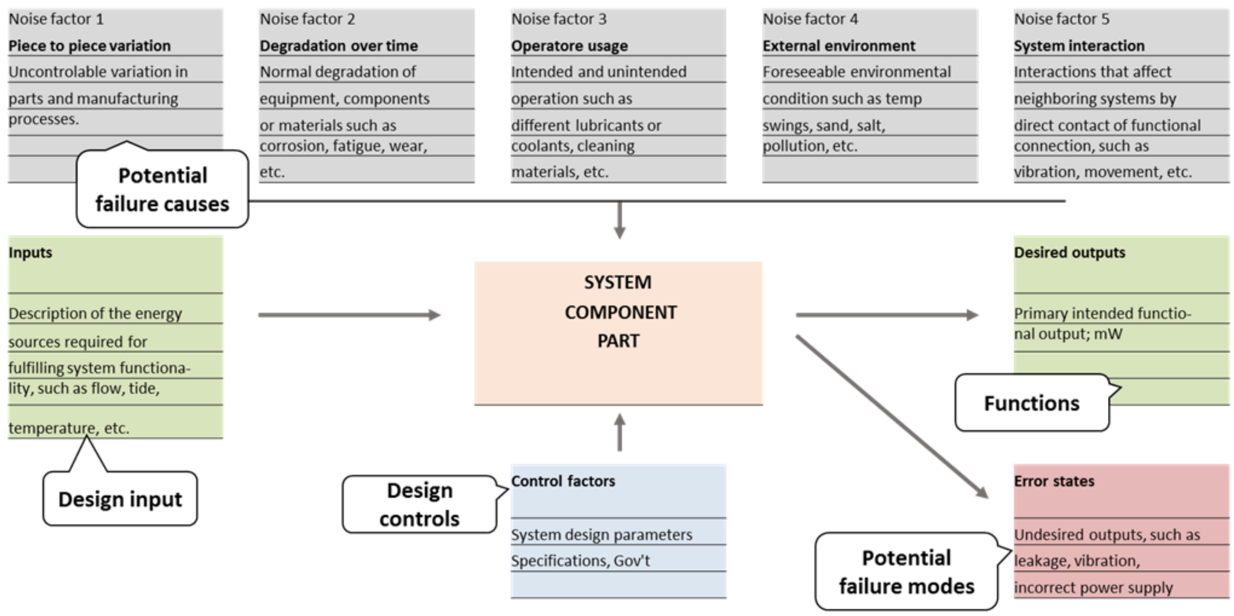

Figure 1: Parameter diagram

6. Occurrence

Assign *occurrence ratings* to each of the causes:

Occurrence ranking table

Likelihood of failure	Criteria Occurrence of cause (design life/reliability of product)	P_{pk}	Criteria Occurrence of cause (incidents per product)	Ranking
Very high	New technology/new design with no history	< 0,55	> 100 per thousand (>1 in 10)	10
High	Failure is inevitable with new design, new application, or change in duty cycle/operating conditions	≥ 0,55	50 per thousand (1 in 20)	9
	Failure is likely with new design, new application, or change in duty cycle/operating conditions	≥ 0,70	20 per thousand (1 in 50)	8
	Failure is uncertain with new design, new application, or change in duty cycle/operating conditions	≥ 0,80	10 per thousand (1 in 100)	7
Moderate	Frequent failure associated with similar designs or in design simulations and testing	≥ 1,00	2 per thousand (1 in 500)	6
	Occasional failure associated with similar designs or in design simulations and testing	≥ 1,25	0,5 per thousand (1 in 2000)	5
	Isolated failures associated with similar designs or in design simulations and testing	≥ 1,40	0,1 per thousand (1 in 10 000)	4
Low	Only isolated failures associated with similar designs or in design simulations and testing	≥ 1,50	0,01 per thousand (1 in 100 000)	3
	No observed failure associated with similar designs or in design simulations and testing	≥ 1,60	0,001 per thousand (1 in 1 000 000)	2
Very low	Failure is eliminated through preventive control(s)	≥ 1,67	0	1

Table 2: Occurrence ranking (note: this table is to be customized for this project)

7. Design controls

List the *design controls* which are in place to either prevent or detect the cause of failure, or the failure mode (or controls which are being or have been used with similar designs). Note that monitoring during operation or preventive maintenance are no form of design control.

Some examples are:

Detection

- Design reviews.
- Prototype testing.
- Validation testing.
- Simulation of design.
- Design of Experiments/Reliability Testing.
- Mock-up using similar parts.

Prevention

- Benchmarking studies.
- Fail safe designs.
- Design and material standards (internal and external).
- Documentation – best practices, lessons learned from previous designs.
- Simulation of concepts.
- Error-proofing.

8. Detection ratings

Assign ratings to each of the design controls.

Detection ranking table

Opportunity for detection	Design criteria: Likelihood of detection by design control	Ranking	Detection	Criteria	Inspection types			Suggested range of detection methods
					Error-proofed	Gauging	Manual inspection	
No detection opportunity	No current design control; cannot detect or is not analysed	10	Almost impossible	Absolute certainty of non-detection			X	Cannot detect or is not checked
Not likely to detect at any stage	Design analysis detection controls have a weak detection capability. Virtual analysis (e.g. CAE, FEA, etc.) is not correlated to expected actual operating conditions	9	Very remote	Controls will probably not detect			X	Control is achieved with indirect or random checks only
Post design freeze and prior to launch	Product verification after design freeze and prior to launch with pass/fail testing (sub-system or system testing with acceptance criteria such as ride and handling, shipping, evaluation, etc.)	8	Remote	Controls have poor chance of detection			X	Control is achieved with 100% visual inspection only
	Product verification/validation after design freeze and prior to launch with test to failure testing (sub-system or system testing until failure occurs, testing of system interactions, etc.)	7	Very low	Controls have poor chance of detection			X	Control is achieved with 100% visual inspection run two times (200%)
	Product verification/validation after design freeze and prior to launch with degradation testing (sub-system or system testing after durability test, e.g. function check)	6	Low	Controls may detect		X	X	Control is achieved with charting methods, such as SPC (Statistical Process Control)
Prior to design freeze	Product validation (reliability testing, development or validation tests) prior to design freeze using pass/fail testing acceptance criteria for performance, function checks, etc	5	Moderate	Controls may detect		X		Control is based on variable gauging after parts have left the station, or Go/No Go gauging performed on 100% of the parts after parts have left the station
	Product validation (reliability testing, development or validation tests) prior to design freeze using test to failure (e.g. until leaks, yields, cracks, etc.)	4	Moderately high	Controls have a good chance to detect	X	X		Error detection in sub-sequent operations, OR gauging performed on set-up and first piece check (for set-up causes only)
	Product validation (reliability testing, development or validation tests) prior to design freeze using degradation testing (e.g. data trends, before/after values, etc.)	3	High	Controls have a good chance to detect	X	X		Error detection in-station or error detection in sub-sequent operations by multiple layers of acceptance: supply, select, install, and verify (pairing operation - axial clearance). Cannot accept discrepant parts
Virtual analysis correlated	Design analysis/detection controls have a strong detection capability. Virtual analysis (e.g. CAE, FEA. etc.) is highly correlated with actual or expected operating conditions prior to design freeze	2	Very high	Controls almost certain to detect	X	X		Error detection in-station (automatic gauging with automatic stop feature). Cannot pass discrepant parts. SWC fully employed
Detection not applicable; failure prevention	Failure cause or failure mode cannot occur because it is fully prevented through design solutions (e.g. proven design standard, best practice or common material, etc.)	1	Very high	Controls certain to detect	X			Discrepant parts cannot be made because item has been error-proofed by process/product design

Table 3: Detection ranking (note: this table is to be customized for this project)

9. RPN

Calculate the *risk priority number (RPN)* = Severity x Occurrence x Detection.
Prioritize the risks. It is recommended that action is taken for risks where the severity is 9 or 10 (regardless of the RPN).

10. Action plan

Generate an action plan for the highest priority risks (up to what RPN range is to be determined in consultation with manufacturer)

The RPN can be reduced by doing one or more of the following:

- Reducing the severity of the effect – by making a design revision.
- Reducing the likelihood of occurrence by:
  - Error proofing the design to eliminate the failure mode.
  - Revising the design geometry and tolerances.
  - Revising the design to lower the stresses or weak components.
  - Adding redundancy.
  - Revising the material specification.
- Improving the controls (prevention or detection) by:
  - Using Design of Experiments to understand which inputs cause variation in the outputs, and implementing controls on the inputs.
  - Revising the test plan.
  - Improving the measurement system using Measurement Systems Analysis techniques.

11. Actions

Note the actions in the relevant column of the DFMECA, and assign an owner and completion date to each.

Once the action has been completed, enter the details and recalculate the RPN to ensure that it has reduced to an acceptable level.

3 Scope

The DMFECA is meant to cover the asset configuration of the entire tidal energy array. It excludes associated tooling for Manufacturing, Operations & Maintenance (e.g. Nacelle Launch And Recovery System).

The process outlined above will be implemented at suitable stages of design development, as and when the design of each part of the array is sufficiently defined to enable meaningful analysis to be undertaken. These elements will be included in further revisions of the report.

The scope of the array's asset configuration is represented by the suggested Product Breakdown Structure (to be refined and validated as the project progresses):

1. Turbine Nacelle
   1.1. Blades and hub

1.2. Shaft seals and bearing
1.3. Flexible coupling
1.4. Gearbox
1.5. Brake
1.6. Generator
1.7. Power Take Off system

2. Nacelle Cable Connection system
   2.1. Electrical connectors
   2.2. Communication connectors
   2.3. Mechanical / structural connection
   2.4. Seals

3. Turbine Foundation
   3.1. Main Structure
   3.2. Ballast
   3.3. Lifting points (for deployment and retrieval)
   3.4. Nacelle Interface
   3.5. Feet

4. Array architecture
   4.1. Subsea cable
   4.2. Subsea hub
   4.3. Export cable
   4.4. Onshore electrical equipment

4 Design FMECA of the shaft seal and bearing unit

The boundary diagrams below show the parts of the array (figure 2) and the ‘shaft seals and bearing’ of the NOVA M 100 turbine (figure 3).

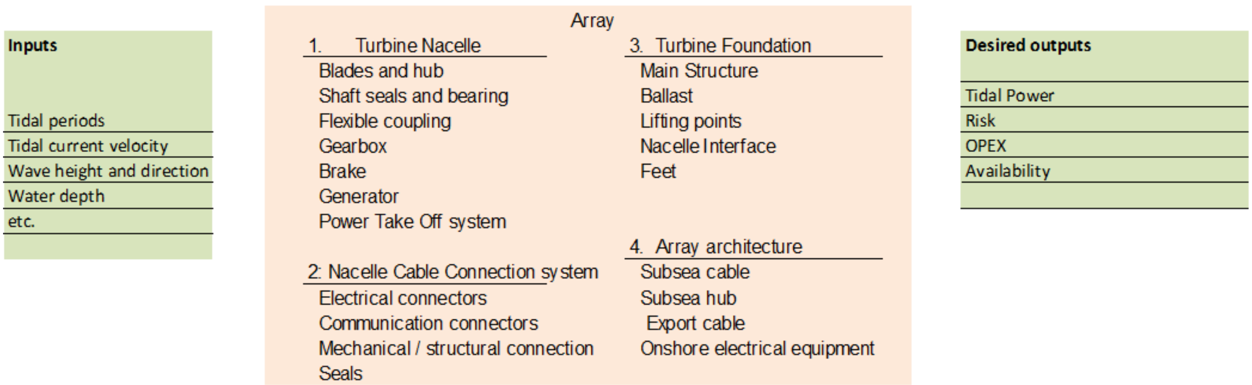

Figure 2: System boundary diagram ‘Array’

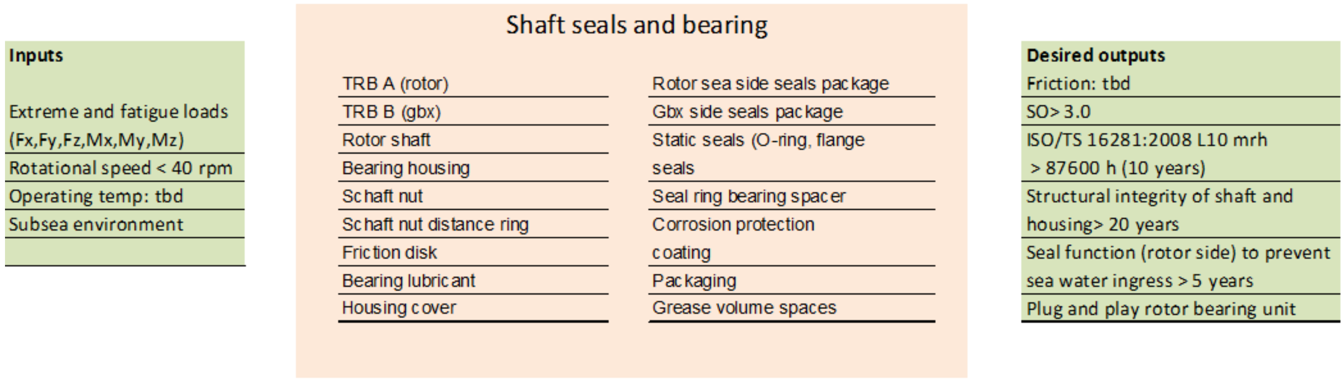

Figure 3: Boundary diagram ‘shaft seals and bearing’

The results of the DFMECA which was executed on the shaft seals and bearing unit are presented in the DFMECA deliverable in Appendix I.

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