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Outlining a Design Process for a Winch- Based Point Absorber Wave Energy Converter

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Abstract

Wave energy has an immense potential to provide clean electricity with almost zero emission, among the many renewable energy resources. While it has a huge potential to cater 10% of the current electricity demand, there are many uncertainties involved in the development of a wave energy converter (WEC). This article discusses those challenges and benefits of a product development process to address them. A winch based point absorber (WBPA) concept being developed at KTH Royal Institute of Technology has been used as reference for all discussions. A systematic design approach provides an effective way to rationalize the project from start to end. The value analysis approach is quite useful in order to eliminate rudimentary functions thereby reducing the cost. The stage gate methods makes the systematic design approach interactive and provides an understanding if a concept must be eliminated or continued with at an early stage in the project. Elements of value analysis approach and stage gate methods have been implemented along side complementing the systematic design approach to outline a design process for the WBPA- WEC. An effort has been made to address the challenges faced in the development of a WBPA- WEC.

Keywords: Winch based point absorbers (WBPA), Wave Energy Converters (WEC), systematic design, value analysis approach, function structure, product developemt process

1 Introduction

Wave energy plays a major role in addressing the transition of electricity generation from fossil fuel to renewable energy. The total wave energy is of the same magnitude as the world electricity consumption i.e., *~ 2 TW*. Around *10- 25%* of the wave energy resource can be harnessed to produce electricity (Cruz, 2008) (Edenhofer, o.a., 2012) (Gunn & Williams, 2012). The large oscillations that can travel long distances without significant loss make for a huge advantage of wave energy. It can either be harnessed off- shore, near shore or on shore which gives significant flexibility to develop a wave energy converter. The point absorbers have the capacity of generating around *1 MW* even though they can be the fraction of a size of the wavelength (Cruz, 2008).

The industrial and academic research has been contributing a significant amount towards making the concept to harness wave energy viable (Reikard, Robertson, & Bidlot, 2015).

However, there are many challenges in developing wave energy converters that can generate electricity from waves at a competitive cost. There have been many concepts developed during the past decades but none have been fully commercialized. (BDrew, Plummer, & Sahinkaya, 2016) discusses and reviews some of these concepts in depth. The main difficulties lie in the unpredictable marine environment and the fact that waves generate high forces. This necessitates durable mechanical structures, which are efficient at generating electricity at low speeds. Moreover, the wave height is quite fluctuating and during storms, it can reach 10-25 times higher than the average wave height. Hence, a WEC must be dimensioned in order to handle large forces and vertical motions (Hagnestål, Sellgren, & Andersson, 2017).
There are many different concepts of WECs under research. A point absorber is a compact WEC consisting of a floating buoy that is anchored at the seabed, a mechanical power transmission system and a power take- off (PTO) unit. Point absorber WECs have smaller dimensions than the wavelength. They are capable of harnessing electricity from waves larger than the dimensions of their own. The hydrodynamic forces from the waves creates motion of the buoy. Usually the point absorber concepts have a linear PTO unit with a finite stroke length and require significant spaces. During storms, these suffer from very large end- stop forces, generally larger than the damping capacity of the PTO system (Leijon, o.a., 2005). On the other hand, in a winch based PTO unit, the drum dimensions limit the stroke. Normally, it has enough stroke length to avoid end stops and the maximum forces can be solved with the PTO and a pre-tensioning system (Hagnestål, Sellgren, & Andersson, 2017). However, it is quite challenging to design a winch that is durable to sustain 80 million cycles or have a lifetime of 20 years. The electricity generated by a Winch- Based Point Absorber (WBPA) WEC can be maximized by introducing phase control concepts such as latching, reactive control or implementation of air springs (Ulvgård, Sjökvist, Göteman, & Leijon, 2016) (Têtu, Ferri, Kramer, & Todalshaug, 2018). The maximum forces can be reduced significantly by implementing the phase control concepts. This allows for compact design of mechanical systems and at a low levelized cost of energy (LCOE) (Andersson, Hagnestål, & Sellgren, 2019). ***Figure 1*** shows the schematic of the Fred Olsen WBPA- WEC PTO layout (Sjolte, Sandvik, Tedeschi, & Molinas, 2013).

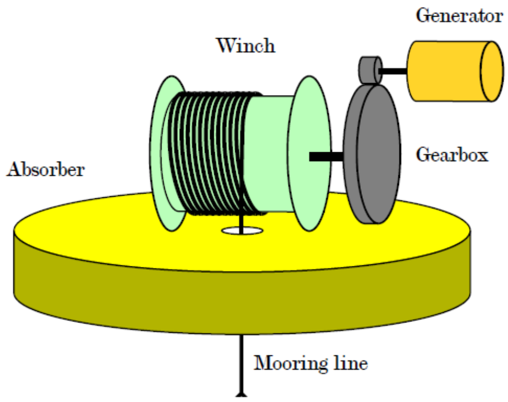

Figure 1: Fred Olsen (Lifesaver) WBPA PTO system (Sjolte, Sandvik, Tedeschi, & Molinas, 2013)

The development of a WBPA WEC requires a feasibility study of the ocean waves at the given location, understanding of ocean characteristics and behavior. This allows the engineer to assess the availability of wave energy and design a WEC that can deliver maximum performance (Falca˜o, 2010). The wave characteristics depends on parameters like the wavelength, its height, water depth, frequency of waves, etc. (Cruz, 2008) (Pecher & Kofoed). The force on the buoy is caused by incident waves which in- turn creates motion of the buoy to generate electricity. The structure present in the path of the waves disrupts its natural flow varying the natural field of flow. It is important to study the interaction between the wave motion and the device. A point absorber must be also be durable to experience and handle external loads and internal loads at the same time be stable enough. The benefit from the absorber system can be maximized if its response is optimized to the wave frequency. A mooring system is implemented in order to prevent the point absorber from drifting away. This system must be able to keep the point absorber stable as well as provide enough degree of freedom for it capture maximum power from the oscillating waves. In addition, reliability and life cycle management must also be considered (Faizal, Ahmed, & Lee, 2014).

To the best of our knowledge, currently, no WBPA exists that can deal with large forces required for efficient phase control. At KTH Royal Institute of Technology, Sweden, a multidisciplinary research collaboration platform for ocean energy has been established to develop such a winch system. An initial prototype of a winch has been developed in 2019 and the progress continues to identify the shortcomings and improve the concept further (Andersson, Hagnestål, & Sellgren, 2019) (Hagnestål, Sellgren, & Andersson, 2017).

As discussed above, WECs are complex system involving many interacting systems and sub-systems. Moreover, marine environment is a very complex playground that demands significantly high amount of capital expenditure (CAPEX) and operational expenditure (OPEX) to enable a WEC that fairly competes with other renewable energy technologies such as wind and solar. Reducing these costs would mean a significant impact on the LCOE for wave energy (Mwasilu & Jung, 2019). A product development process may help overcome these challenges, assist in highlighting the existing gaps in the design and development process and facilitate in the bridging these gaps.

This paper, presents the accessibility of existing product development processes (PDPs) to outline a basic design process for a WBPA and identifies the research challenges. A summary of product development process is described in Section 2. This knowledge is used to outline a PDP for WBPA- WEC that is discussed in detail in Section 3. The PDP is discussed with reference to the WBPA- WEC project ongoing at KTH Royal Institute of Technology. For this purpose, the ongoing project at KTH is taken as reference and the process used in the project has been correlated to the design process.

2 Background

As discussed above, it is established that the development of a WEC involves designing of systems and sub- systems whose functioning is significantly dependent on each other. It has a complex architecture and identifying the risks and uncertainties at an early stage is crucial. Developing a WEC in an efficient and cost effective manner can reduce the lead- time of the entire development process and bring down the LCOE.

Since WEC being a complex system its development includes a fair amount of uncertainties. Incorporating product architecture in the early development phases can save many iterations in the later stage of the development process (Edenhofer, o.a., 2012). A systematic engineering design approach by (Pahl & Beitz, 2007), (Pugh, 1991) and (Ulrich, Eppinger, & Yang, 2020) provides an effective way to rationalize the design process from identification of the market need to selling a successful product. However, it is necessary to encompass the broadest range of solutions on an abstract level since each of them represent a set of different concrete solutions. This saves cost and time that is consumed to develop, describe and evaluate concrete solutions than abstract ones (Damien, 2008).

In order to reach a concrete solution from the abstract ideas, (Pahl & Beitz, 2007) introduces a functional structure that decomposes an overall function into sub- functions. A function determines *what the product must do* while a sub- function conveys *how it should be done* (Damien, 2008). A function can have multiple sub- functions. Whereas (Pugh, 1991), the function decomposition mostly serves the purpose of simplifying a particular task. (Pahl &

Beitz, 2007) approaches a design problem in a structured way by dividing the function into multiple sub- functions and shortlisting the most promising one as compared to (Ulrich, Eppinger, & Yang, 2020) and (Pugh, 1991) who encourage a more creative way and brainstorming to generate multiple concepts.
(Pahl & Beitz, 2007) complements the systematic design approach with value analysis approach. This focuses on minimizing the functional cost by elimination of unnecessary functions. Based on the scope of the depth of complexity it includes, (Wynn & Clarkson, 2018) classifies the development process into micro, meso and macro levels. Meso-level procedural models aim to support the effective generation of good designs by prescribing a systematic design process. (JH, 1959) developed a spiral form to highlight that the design process is iterative. He believed that, a design process cannot be sequential and a structured iterative procedure is necessary to resolve the trade- offs between interdependent factors. Early estimates are made and refined continuously as the project progresses (Cooper, 2014).
Based on the above discussion, an initial outline of design process for WBPA has been presented in ***Figure 2***. The project begins with identification the requirements and demands that determines the scale of the product. Further, based on the requirements, the WEC is divided into three basic components- the transmission, PTO unit and mooring to populate the product design specification (PDS). To quantify the requirements in the PDS, information from initial concept modelling is included which the backbone for further development of the product. All the different technical elements i.e., hydrodynamics, mechanical and electrical components, control systems, etc. are intertwined with each other and are therefore combined together in the design development phase. Lastly, as with any product, testing and prototyping is crucial to identify any errors before the launch of the actual product.

3 Implementation of PDP in WBPA- WEC development

The PDP presented by Pahl & Beitz, Pugh and Ulrich & Eppinger have been used as a baseline to outline the design process in ***Figure 2***. Further into the design process, the stage gate process (Cooper, 2014) has been incorporated at each step to make it more iterative and determine if the chosen function or sub- function structure is the potential solution to the problem statement. In addition, other important factors such as reliability and sustainability, life cycle management, ease of installation, maintainance and serviceability, safety, etc. must be taken into consideration. The safety must always be ensured as the marine environment is quite dangerous (Mccormick, 2007).

3.1 Requirements Identification

Requirements are essential to form a system boundary and underline the necessary functions and task-specific constraints. Some of the initial requirements include knowing the targeted WEC size and operating conditions (Cruz, 2008). These requirements together form the base for product design specification (PDS). It is a living document that keeps evolving based on the developments in the project to reflect the final state of the design (Pugh, 1991).
It must be noted that in this paper, with reference to ongoing project at KTH, only the design process of the winch is discussed.

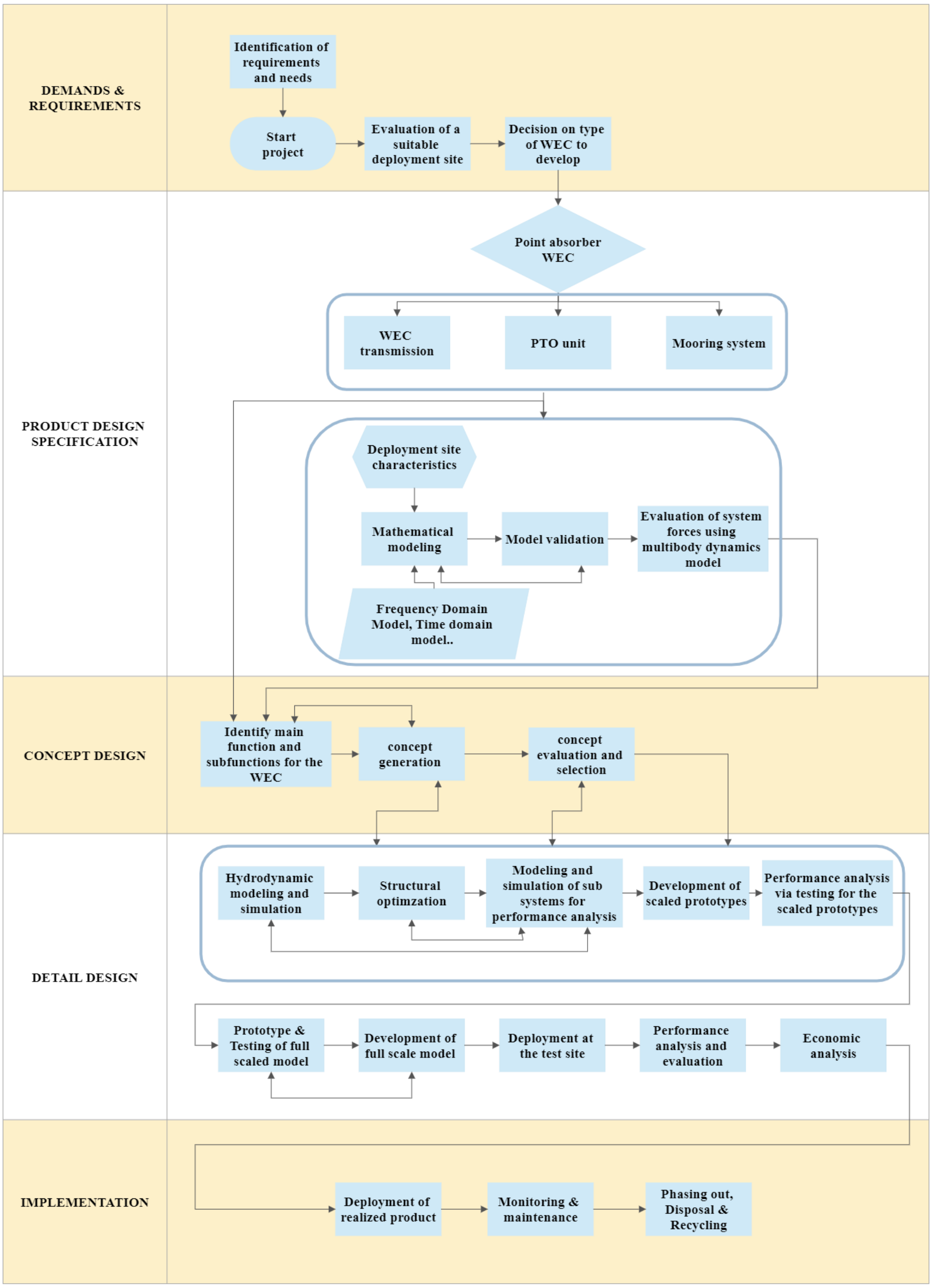

Figure 2: A Design Process outline for development of WBPA- WEC based on learnings from (Cooper, 2014), (Pahl & Beitz, 2007), (Pugh, 1991), (Ulrich, Eppinger, & Yang, 2020) & (J.C.C.Portillo, o.a., 2020)

For the development of a winch solution, the formulated preliminary requirements are listed in ***Table 1***. It contains the requirements for two different scales- a 1/10 force scale aimed at operating conditions in the Baltic seas with smaller waves while the full scale for North Atlantic sea (Hagnestål, Sellgren, & Andersson, 2017).

Table 1: Preliminary requirements for winch based on (Andersson, Hagnestål, & Sellgren, 2019) & (Hagnestål, Sellgren, & Andersson, 2017)

Winch unit	*1/10 force scale*	*Full force scale*
Maximum stroke	25 m	37 m
Peak vertical speed	7 m/s	8 m/s
Typical speed (peak)	0.5-2 m/s	3-4 m/s
Maximum force	200 kN	2000 kN
Winch efficiency	> 97%	> 97%
Requirements from operational environment	Resistance to corrosion, biofouling	Resistance to corrosion, biofouling
Environmental impact	No leakage of non-biodegradable fluids	No leakage of non-biodegradable fluids
Design life	20 years, 80 million cycles	20 years, 60 million cycles
Service intervals	> 5 years	> 5 years
Winch width	< 2 m	< 3 m

3.2 Conceptual Design

Once the crux of the task is established, the project progresses into the concept design phase as underlined ***Figure 2***. Initial step includes development of function structure. The requirements determine the overall function. This reduces the complexity of the entire problem and its formulation. It gives the designer a good understanding of the overall working principle of the system. It is important to establish a good relationship between the inputs and the outputs, details of the necessary physical processes and the number of components and assemblies needed to achieve the overall task. This facilitates in providing better solutions with the help of a simple and explicit function structure (Pahl & Beitz, 2007). As an example, an initial function structure of a WEC is shown in ***Figure 3***.

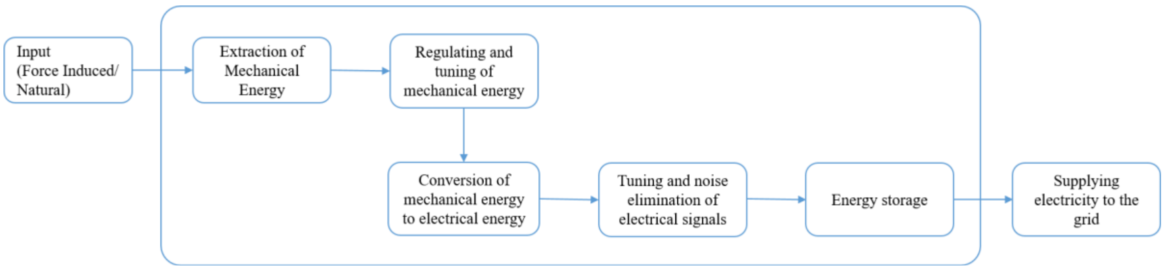

Figure 3: Preliminary function structure of a WEC

In a WBPA- WEC *extraction of mechanical energy* in ***Figure 3*** is achieved via a winch system. The winch system is further divided into a preliminary sub- function structure in ***Figure 4***. This sub- function structure can also be divided further in a similar fashion to reduce the complexity of the system.

Winch system	Linear motion	Handling the degrees of freedom for efficient force transmission
		Force transmission system (ropes, cables, chain, etc..)
	Anchoring	Mooring
		Connection interface to the mooring system
	Pre-tensioning	Spring system
		Use generator as motor
	Connection to the PTO	connect and disconnect mechanism
		System to scale up the input torque
		Locking mechanism in case of storms

Figure 4: Preliminary sub- function structure for a winch system

Some of the initial challenges for developing a durable winch include determining the degrees of freedom for the movement of winch without twisting the force transmitter. In addition, as discussed earlier in section 1, a larger drum allows for larger stroke length while to reduce the torque and maximize the rotational speed, the size of the drum must be minimized. These challenges have been discussed in detail in (Hagnestål, Sellgren, & Andersson, 2017). A schematic of the winch system along with coordinate axes representation is shown in ***Figure 5***.

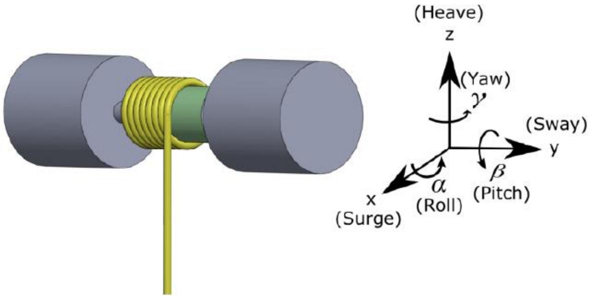

Figure 5: Schematic of a winch with corresponding coordinate axis when aligned with the waves (Hagnestål, Sellgren, & Andersson, 2017)

3.2.1 Conceptual Designing of the force transmission system

The components of concept design includes concept generation and evaluation as referred to in ***Figure 2***. Here, five different concepts have been evaluated using Pugh's matrix (Lingaiah, Deshpande, Wigardt, & Colazio, 2017). These concepts are listed below:

- Reference (A): Stainless steel wire for marine applications.
- Dyneema rope (B): It is made of high performance, high modulus and ultra-high molecular weight polyethylene with yield strength of 2.4 GPa.
- Multiple links (C): An elastic membrane is attached between the pin and the link. When subjected to force, the membrane is deformed elastically, without sliding. These links can be either stress confined (C1) or have flexible elastomer pins with grooves (C2).

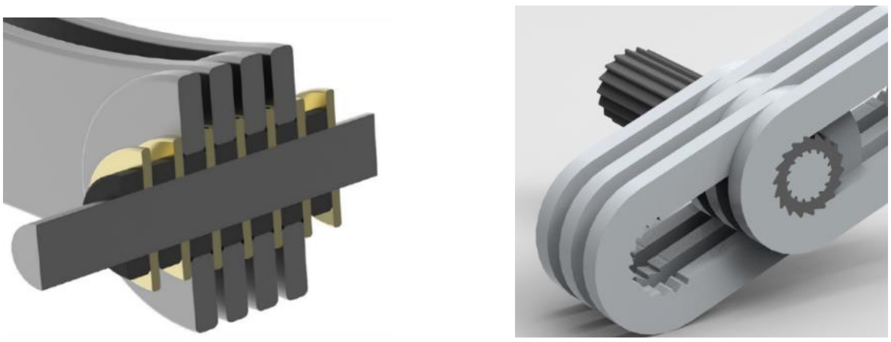

Figure 6: Multiple links- confined stress (left); multiple links with flexible elastomer pins (right) (Lingaiah, Deshpande, Wigardt, & Colazio, 2017)

- Sealed roller chain (D): This concept is based on a heavy-duty roller chain embedded in watertight coating. Existing roller chains lack fatigue performance desired in marine environments.
- Carbon fibre rope (E): The concept is to pultrude carbon fibres in a unidirectional way and enclose them in a waterproof package with lubrication inside.

These concepts have been evaluated using Pugh matrices and multiple links with confined stress is chosen to develop further as shown in ***Table 2***. The criteria included in the evaluation are based in order to address the challenges. This helps to understand if a concept has the potential to provide a solution.

Table 2: The initial (left) and final (right) Pugh's matrix for evaluation of concepts (Lingaiah, Deshpande, Wigardt, & Colazio, 2017).

Criteria	*A*	*B*	*C1*	*C2*	*D*	*E*
Fatigue life	0	0	1	1	0	1
Wear resistance	0	-1	1	1	1	1
Tensile strength	0	0	0	0	0	1
Bending performance	0	1	1	1	1	0
Corrosion resistance	0	1	1	1	1	1
Complexity	0	0	-1	-1	-1	-1
Manufacturing	0	0	-1	-1	-1	-1
Innovation	0	0	1	1	0	1
Price	0	0	-1	-1	-1	-1
Sum 1	0	2	5	5	3	5
Sum 0	9	6	1	1	3	1
Sum -1	0	1	3	3	3	3
Net value	0	1	2	2	0	2
Rank	3	2	1	1	2	1
Further development	No	No	**Yes**	**Yes**	No	No

Criteria	*C1*	*C2*
Fatigue life	1	0
Wear resistance	0	0
Tensile strength	1	0
Bending performance	0	1
Sub marine performance	0	0
Complexity	0	-1
Viability	0	0
Innovation	0	0
Price	0	-1
Sum 1	2	1
Sum 0	7	6
Sum -1	0	2
Net value	2	-1
Rank	1	2
Further development	**Yes**	No

The carbon fibre concept does score similar points to multiple links however, needs more research in carbon fibres and the manufacturing of these.

3.3 Detail Design/ Embodiment Design

The concept development is followed by detail design, refer ***Figure 2***. To begin with, the challenges faced in the design development are listed and effort has been made to address them.

3.3.1 Elastomer Bearing and Chain Link Design

The requirements in ***Table 1***are used to design and dimension the chain and elastomer bearings. Moreover, there are a few design challenges identified.

- The forces in the link configuration must be distributed such that the chain is durable enough to withstand fatigue life
- The material selected for the chain link must resist corrosion and survive the harsh marine environment
- The link configuration must be designed such that the bearings experience reasonable compression strain
- The elastomer bearing must be stiffer in tension and compression compared to in shear
- The bearing must be flexible enough to provide some angular movement between the links
- Since an elastomer is a non- linear material, it is a challenge to determine the correct material properties for further calculations and evaluation of the elastomer bearing design

Based on the above criteria and boundary conditions, a flowchart illustrating the crucial steps in the design process for development of chain and elastomer bearing has been outlined in ***Figure 7***.

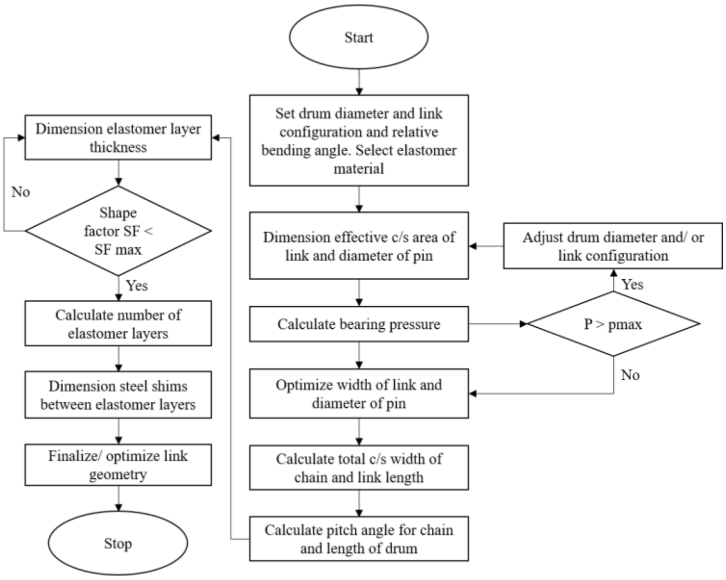

Figure 7: Illustration of design process for development of chain and elastomer bearing (Andersson, Hagneståł, & Sellgren, 2019)

These boundary inputs and the design process have been followed along with (Gent, 2012) as guidance to develop the chain links and elastomer bearing. Structural optimization and FEA analysis are used to finalize and optimize the chain design. Duplex stainless steel EN 1.4462 with yield strength of 500 MPa is chosen for the chain. To divide the force, a 2+3 chain link configuration has been proposed. To make the bearing stiffer, alternate layers of rubber and steel shims are suggested. The current bearing has 4 layers of elastomer and 3 layers of steel shims. Since the link is wound around a drum, an angular movement of 5° on either side has been considered while designing the bearing. The detailed calculation and design procedure for the bearing and the chain link has been laid out in (Andersson, Hagneståł, & Sellgren, 2019).

3.3.2 Verification and Testing

Elastomer is both an elastic and viscous material. It is incompressible and depicts highly non-linear behavior. Hence, a non- linear FEA analysis using hyper elastic material models is required in order to analyze and verify the elastomer bearing design. Material constants are needed as input to model accurately model an elastomer (Gent, 2012). These material constants are obtained from material tests. Two different materials samples– silicone and polyurethane of 1mm thickness each were tested. A circular elastomer sample with 23 mm and 25 mm as inner and outer radius respectively was used. The sample was compressed by 50% and sheared upto 0.5°. ***Figure 8*** shows the compression stiffness of silicone and polyurethane. Cyclic load was applied and the compression was increased by 10% at every step until 50% compression was reached. It can be observed that with each cyclic load step, the material becomes softer. This means that the material has not obtained enough recovery time between the load steps. This is defines as *Mullins Effect,* which determines the damage caused in the material otherwise referred as *hysteresis*. The softening effect is lower in polyurethane compared to in silicone. ***Figure 9*** shows the shear stress for both the materials. Polyurethane is stiffer in shear compared to neoprene. It is desired that the elastomer material is stiffer in compression as compared to shear. In that regard, polyurethane seems promising but, more research and testing is required to confirm this behavior.

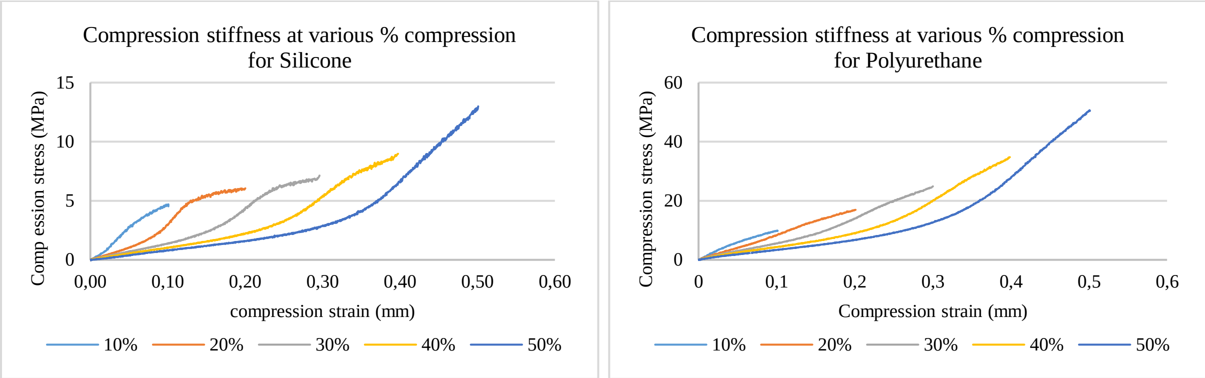

Figure 8: Compression stiffness for Silicone (left) and Polyurethane (right)

A curve fitting analysis is used to extract the material constants. This data is used as an input for FEA modelling to further analyze and evaluate the bearing design.

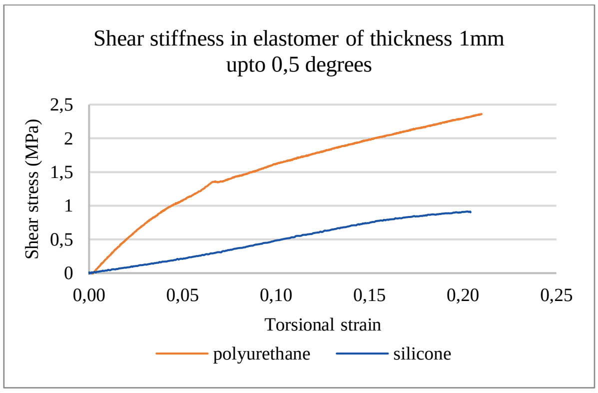

Figure 9: Shear stiffness for Silicone and Polyurethane

For further verification of the data obtained in ***Figure 8*** and ***Figure 9***, a test rig has been developed to measure the stiffness of the elastomer bearing. When the link is wounds around the drum, the bearing would undergo shearing load. The main purpose of the test rig is to shear the rubber in the elastomeric bearing while the link is tensioned (Lingaiah, Deshpande, Wigardt, & Colazio, 2017). The preliminary test rig set up has been shown in ***Figure 10*** (right).

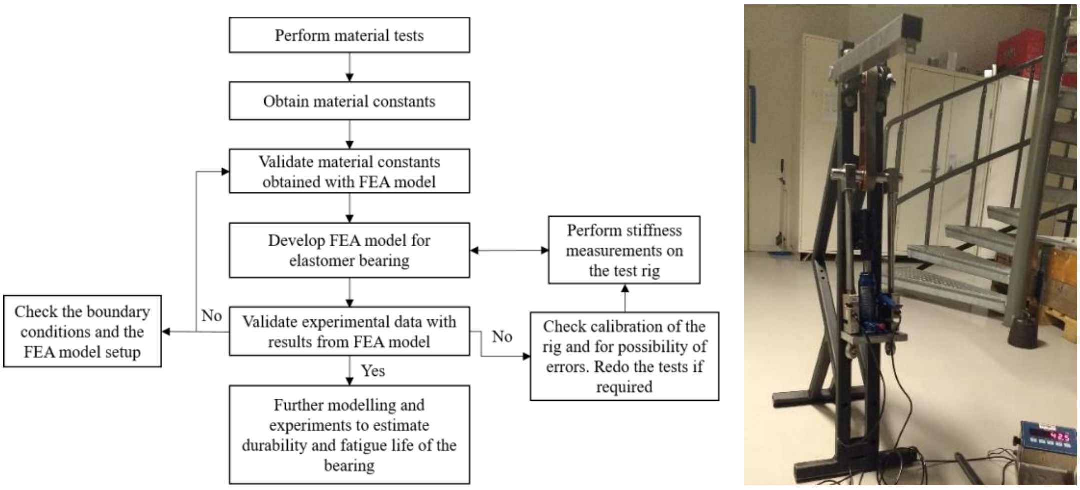

Figure 10: Steps for verification of the bearing (left); Test rig set up for measuring bearing stiffness (right) (Andersson, Hagnestål, & Sellgren, 2019)

4 Future Work and Conclusions

4.1 Future Work

For future work, further testing to determine the stiffness of the bearing and development of a robust numerical model for the elastomer bearing is required. In addition, tests and detailed analysis must be pursued for the entire winch setup with the chain wound around the drum.

4.2 Conclusions

In this article, a generic baseline design process has been outlined for the development of a WBPA- WEC. The existing PDPs have proved very useful to provide a guiding thread to designers. As presented in section 3, to approach the designing of a winch system, it is divided into sub- function structure to simplify the problem statement. The challenges listed in section 3.3 are solved with the assistance of a functional diagram. However, few gaps and drawbacks have been recognized. As new elements are added into the design, the function structure is bound to change. Moreover, it is very difficult to select a solution just based on abstract technical criteria without including some parts of detail/ embodiment design like material selection and basic structural calculations. For instance, as referred in ***Figure 2***, to define the PDS for WBPA, basic calculations need to be performed using mathematical modelling and numerical analysis. This applies also if economic criteria are to be considered during selection of a solution which would require understanding the feasibility and manufacturability of the concept. These gaps and drawbacks have also been addressed in (Damien, 2008).

5 Acknowledgement

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