TWO-DIMENSIONAL TENSION ANALYSIS OF SUBSEA CABLE USING MINIMIZATION WITHOUT GRADIENT BASED TECHNIQUE

NUR AZIRA BINTI JASMAN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Science
Universiti Teknologi Malaysia

JULY 2021

DEDICATION

This thesis is dedicated to my lovely parents, family and friends

ACKNOWLEDGEMENT

In the name of Allah, The Most Gracious and The Most Merciful. All praises to Allah s.w.t. who has blessed me with the belief, the strength and capabilities to write this thesis. Without his grace this research could not become a reality.

First of all, I would like to express my sincere gratitude to my supportive supervisor, Assoc. Prof. Dr. Yeak Su Hoe for always giving ideas and suggestion. His constant determination on teaching, advising and encouraging me during the process of completing the research have made this journey become much more enjoyable. I would also like to say thank you to my co-supervisor, Dr. Mohd Ridza Mohd Haniffah for his time and advice throughout this journey.

I also would like to extend my appreciation to the Ministry of Higher Education for providing me with the MyBrainSc Scholarship in financial support for this whole journey.

Finally, to my parents, thank you so much for the warm love and support throughout this journey. To my dearest friend Adlin Lina, and all family members, you guys have been the best supporters. Thank you so much. May Allah always grant us with his blessing and love forever.

ABSTRACT

Subsea telecommunication cable has been used extensively since the 1850's and the deployment of subsea cable continues to be a risky and challenging operation encountered by engineers due to many uncertainties. Analysis of subsea cable tension is very important in the design stage, to ensure that the cables are laid out according to plan. A free hanging subsea cable that is connected from a floating vessel to the seabed, has been known to be the most common configuration deployed near to platform. However, this conventional configuration produces a large hang-off load on the subsea cables which could potentially cause buckling issues at touchdown point. An alternative configuration is created by considering the use of buoyancy module attached to certain parts of the subsea cable in order to reduce stress and avoid failure. In this research, the formulation of mathematical model in steady state condition related to the free hanging subsea cable configuration is improved on obtaining the top tension by considering a single point moment at the top node based on the physical law of subsea cable. The linear element of subsea cable is introduced by discretizing the cable element on each region accordingly. The mathematical model for the conventional configuration is developed as the first step to improve the analysis of subsea cable tension problem and to provide an insight on the position of maximum tension produced on the cable. The mathematical model obtained is then extended for the configuration with buoyancy module attached to the subsea cable. Tension analysis for both subsea cable configurations, were solved using minimization without gradient-based technique. This technique produces results that converge to exact solution considering the implementation of additional assumption and condition on the formulated mathematical model. The conventional subsea cable configuration shows maximum tension at the hang-off section, a situation that causes extreme stress on the subsea cable. However, the new subsea cable configurations developed in this research have been shown to reduce the subsea cable tension, especially at the hang-off section. In conclusion, a single buoyancy module attached to specific position on the subsea cable could reduce the extreme stress of cable and prevent cable breaks.

ABSTRAK

Kabel telekomunikasi bawah laut telah digunakan secara meluas sejak tahun 1850 dan penggunaan kabel ini merupakan operasi yang berisiko serta mencabar bagi para jurutera kerana pelbagai ketidakpastian. Analisa ketegangan kabel bawah laut sangat penting dalam peringkat reka bentuk, bagi memastikan kabel diletakkan mengikut perancangan. Kabel bawah laut yang tergantung secara bebas yang disambungkan daripada sebuah kapal terapung ke dasar laut merupakan konfigurasi yang paling biasa digunakan berhampiran pelantar. Namun, konfigurasi konvensional ini menghasilkan beban tergantung yang sangat besar pada kabel dan berpotensi menyebabkan masalah ketidakstabilan pengancing pada titik sentuhan bawah laut. Konfigurasi alternatif direka dengan mempertimbangkan penggunaan modul keapungan yang diletakkan pada bahagian tertentu kabel bagi mengurangkan tekanan dan mengelakkan kegagalan. Dalam kajian ini, ketegangan teratas model matematik bagi kabel bawah laut yang tergantung secara bebas dalam keadaan pegun dirumuskan dengan mempertimbangkan penggunaan satu titik momen pada nod dasar laut berdasarkan hukum fizik kabel. Unsur linear pada kabel bawah laut diperkenalkan dengan membahagikan elemen kabel kepada beberapa kawasan dengan sewajarnya. Model matematik untuk konfigurasi konvensional dihasilkan sebagai langkah pertama untuk memperbaiki analisa masalah ketegangan kabel dan memberikan pandangan tentang kedudukan maksimum ketegangan kabel. Model matematik yang diperolehi kemudiannya dikembangkan untuk konfigurasi yang menggunakan modul keapungan yang diletakkan pada kabel bawah laut. Analisa ketegangan kabel untuk kedua-dua konfigurasi telah diselesaikan menggunakan teknik minimasi tanpa kecerunan. Teknik ini menghasilkan jawapan yang menumpu kepada penyelesaian tepat dengan mempertimbangkan syarat dan andaian tambahan pada model matematik yang dirumus. Konfigurasi konvensional menunjukkan ketegangan maksimum di bahagian tergantung, keadaan yang akan menyebabkan tekanan melampau pada kabel. Namun, konfigurasi baru bagi kabel yang dibentuk dalam penyelidikan ini telah menunjukkan pengurangan ketegangan kabel terutamanya pada bahagian yang tergantung. Kesimpulannya, satu modul keapungan yang diletakkan pada kedudukan khusus di kabel dapat mengurangkan tekanan kabel yang melampau serta mengelakkan kabel putus.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

TDP	-	Touchdown Point
FDM	-	Finite Different Method
FEM	-	Finite Element Method
BEM	-	Boundary Element Method
SLWR	-	Steel-Lazy Wave Riser

LIST OF SYMBOLS

r	-	The radius of subsea cable, where $d = 2r$ is the diameter of subsea cable.
g	-	Gravitational acceleration.
W	-	Self-weight of a cable per unit length in water.
$T_{x_i}(s)$	-	Tension force at i^{th} point in the x-direction.
$T_{y_i}(s)$	-	Tension force at i^{th} point in the y-direction.
ρ_c	-	Density of subsea cable.
ρ_w	-	Density of seawater.
$\rho g \Delta s$	-	Gravity of cable segment Δs, $\rho = \pi r^2 \rho_c$.
$\rho_o g \Delta s$	-	Buoyancy of cable segment Δs, $\rho_o = \pi r^2 \rho_w$.
D_x	-	Drag force of seawater in the x-direction.
D_y	-	Drag force of seawater in the y-direction.
L_x	-	Lift force of seawater in the x-direction.
L_y	-	Drag force of seawater in the y-direction.
H	-	Water depth.

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Subsea optical fiber cable has been available since early of 1850's and has been extensively constructed worldwide. Subsea cables have been used to carry telegraphy traffic, and can thus be called the first instant telecommunication link. Subsea cable is placed on the sea bed between one land based station to another in order to carry telecommunication signals across stretches of ocean and sea. As stated by Yang *et al.* (2013), rapid development of telecommunication systems has led to the exploitation of the ocean environment resources in order to ensure the intensive deployment process of subsea cable. Marine environment may be very complicated and inconsistent in some region. Thus, the operation of subsea cable deployment process is a crucial stage where any incorrect manipulation of the process will tend to produce irreparable damage to the subsea cable.

According to Xiang *et al.* (2016), subsea cable laying is a common process for engineers including installation of cable. In modern industry, these cables are used for telecommunication, marine petroleum exploitation and as power cables. Subsea cable installation process is extremely important in life time process involving the consideration of cable profile and the ocean environment in order to avoid any detrimental effects on the cable. The laying process requires very precise control as today's modern cables are made of fiber optics technology to carry digital data including internet and private data traffic. Wastage of budget will occur whenever issues arise when the cable being laid is not controlled properly.

One of the challenges faced during subsea cable laying process is the formation of slack (Abidin *et al.*, 2018). Slack that formed during the laying process of subsea cable will increase the possibility that the cable being laid is too long, where cable being laid not exactly according to the plan route and cause buckling issues at the touchdown point (TDP). The problem of uncontrolled slacks also leads to the wastage of budget. This situation will make detection of cable break locations to be inaccurate and lead to increase in cable break instances. Therefore, for certain vessels to operate, it is very necessary to control the residual tension of the cable and determine the most convenient cable configuration in order to avoid any slack on the cable.

As it may not be possible to develop analytical solutions of practical engineering problems, numerical method is chosen and developed due to its ability to obtain an approximate solution of many types of engineering problems. Numerical method is the study of algorithm that provide numerical approximation of mathematical analysis generally in real world application. Numerical method is also very important in scientific computing of engineering problems as it allows us to estimate solution to the problems that may be extremely difficult to solve analytically. Most engineering problems are in the form of partial differential equations (PDEs) with certain boundary conditions. In general, solution to these PDEs are very significant due to the practical interest of the solution. It is very important for the expert to develop approximate solutions to the given PDEs as it would help in real world problem, even if it may be very difficult to obtain the closed form of the solution. There are many available numerical techniques that can be used in order to approximate the solution of related problems such as finite difference method (FDM), finite element method (FEM), boundary element method (BEM) and other numerical methods.

The most common numerical methods used in engineering and computational fluid dynamic problems are FDM and FEM. FDM is known as the most dominant approach to numerical solutions of PDE because of its simplicity and thus it is commonly used by engineers as a kick start of solution to the related problem. The idea of FDM is to approximate the differential operator by replacing the derivatives in the equation using differential quotation of forward, backward and central difference equation. However, the usage of FDM is limited and not suitable for spatial discretization of non-rectangular and complex geometries.

As for FEM, it will approximate the values of unknown at discrete number of points over the domain. The analytic solution of problems in related areas of heat transfer, fluid flow and many more would generally require the solution to the boundary value problem. FEM formulation of these problems will lead to a system of algebraic equations. The large problem is then sub divided into simpler parts called finite elements. However, the associated error function produced during the calculation in this method can be minimized by giving some effort in computation, which may require extra work.

At present, various numerical methods have been developed for subsea cable problem in literature such as FDM, FEM and BEM. However, the discretization involved in these methods requires some sort of underlying computational mesh and becomes a difficult task to solve for higher-dimensional problem. Approximation to the partial differential equation of these methods will require solving related problems using time integration technique which will result in increase of error produce in the calculation and make the approximate solution not converging to the exact solution.

1.2 Research Background

According to Wang *et al*. (2013), the configuration and design performance of subsea cable are essential during the design stage of subsea cable installation. A free hanging subsea cable connected from a floating production vessel to the seabed, known as a catenary configuration, has been promoted as an increasingly attractive choice in deep water fields. The catenary configuration of subsea cable form has been an attractive choice as it provides few advantages such as lower manufacturing cost and good ability to resist high temperature. However, this kind of configuration faced a great challenge in harsh environments such as buckling issue at the touchdown zone of subsea cable, which is induced by the fatigue problem due to the vessel motion and hydrodynamic reaction. The catenary configuration is only recommended for systems with less harsh environment and less vessel motion as this kind of shape will also cause high top tension levels.

As catenary configuration of subsea cable is sensitive to fatigue, variation to the catenary configuration is developed by considering the existence of buoyancy module, which has become a logical extension of the catenary configuration by installing several buoyancy modules at a certain part of the subsea cable creating upward buoyancy force to eliminate partial tension of the subsea cable. According to Wang and Duan (2015), buoyancy module equipped on the subsea cable tends to decouple the catenary configuration from surface dynamic in the touchdown region, creating wave shape which ensures the strength, fatigue performance, and platform payload of the cable are within acceptable limits.

According to Bai (2014), subsea cable and pipeline are similar in terms of slender structures and accidental impact loads but differ in terms of local damage mechanism. The subsea cable response towards trawl gears will be dramatically different compared to pipeline due to the flexibility and weight per unit length of the cable. However, the interaction mechanism between subsea cable and trawl gears located on the seabed is similar with pipelines. The subsea cable tension is dominated and behaves like a flexible beam during the pulling process assuming that the towing speed of the floating production vessel is low. Thus, the damage on subsea cable due to the trawls may not be too significant during the initial impact stage.

To date, there are many studies concerning the numerical simulation of the subsea cable problem. However, the majority of papers are mainly focusing on the simplified version of subsea cable configuration, which is subsea cable without buoyancy module with several crucial assumptions and some restrictions on engineering problem. For example, the formulation of linear model was made by eliminating the tangential drag forces and some of them assumed that the cable's elevation angle is constant along the cable (Vaz et al., 1997, Vaz & Patel, 2000, Chucheepsakul et al., 2003, Howison, 2005). Other than that, in many of the cases mentioned above, the use of buoyancy module was ignored in the formulation in order to preserve the simplicity and easy installation of subsea cable (Han et al., 2018). This kind of model is very sensitive to fatigue and present high top tension of subsea cable when being submerged into the ocean.

Most of previous studies on free hanging subsea cable focused on developing mathematical equation on subsea cable tension in which the top and TDP tension are obtained based on free end or fixes conditions without considering the physical law of the cable (Yang *et al.*, 2013). This kind of mathematical equation for this configuration faced a great challenge in harsh environments such as buckling issue at the touchdown zone of subsea cable, which is induced by the fatigue problem due to the vessel motion and hydrodynamic reaction. The analytic solution of complex geometry of subsea cable may not exist or may not be possible to be developed (Park et al., 2003). Thus, numerical analysis of the related problem should be developed as an alternative approach in solving the problem.

Minimization without gradient-based technique provides an approximation to the mathematical analysis solution and may also overcome some drawbacks in the conventional numerical methods such as not suitable for problem with complex geometry (Nocedal & Wright, 1999). Minimization without gradient-based technique has the ability to efficiently find the global minima of the problem even in complex geometry. This method also has the ability to minimize the sum of squares of the residual errors, which make the approximate solution converge to exact solution (Russenschuck, 1999). This technique makes the additive assumption and condition on the formulated mathematical model of related problem possible where it will be more practical and tend to be more similar to the actual situation. This undertaking is essential as it can assist many opportunities to be explored in the future in terms of modelling improvement.

1.3 Problem Statement

Subsea cable deployment is still considered to be very challenging, complex and crucial due to many uncertainties arising due to the nonlinearity of the cable behavior and multiple affecting parameters such as current velocity, water depth and cable diameter. The catenary configuration of subsea cable, which can be described as a free hanging subsea cable connected from a floating production vessel to the seabed, has become a popular configuration used in deployment of subsea cable near the platform as it can provide a low cost alternative of subsea cable design. However, this type of configuration is sensitive to fatigue and produces large hang-off loads which will potentially cause a buckling issue on the subsea cable at the touchdown point zone. The catenary configuration is only recommended for systems with less harsh environment and less vessel motion as this kind of shape will also cause high top tension levels. An alternative to this configuration is developed by considering the implementation of buoyancy module in certain part of the subsea cable in order to reduce the fatigue response and extreme stress of the subsea cable. The dimension of subsea cable geometry with the use of buoyancy module provides an important factor that will control the strength and fatigue performance of a cable. This study is conducted in order to analyze the tension of subsea cable in condition with and without buoyancy module and also to determine a suitable cable configuration for subsea cable deployment in a shallow water condition near the platform area.

Cable wastage during deployment of subsea cable near the platform may occur due to the formation of slack where the cable configuration curves tend to be fatter when cable touches the seabed. In order to control the wastage, the formation of slack needs to be minimized and the vessel movement needs to be synchronized with the cable being laid out. To address this, the optimal cable tension during the deployment of the cable is very important and needs to be determined appropriately. Tension analysis of both types of subsea cable configuration is important in the design process as it will provide an insight into which configuration would be chosen under certain conditions. This study is conducted to provide an analysis of tension distribution along the subsea cable based on the subsea cable configurations with a focus on several performance measures such as position of the vessel, and water depth.

Despite the establishment of FDM, FEM and BEM in subsea cable problem, numerical approach of minimization without gradient-based technique has been chosen in this study as this technique provides an approximation to the mathematical analysis solution by efficiently finding the global minima of the problem even in higher-dimension problem. The formulation of the conventional methods mentioned will lead to a system of algebraic equation that associated with more error produced during calculation and require extra work on minimizing the error which will cause the approximate solution not converging to the exact solution. Thus, numerical approach of minimization without gradient-based technique is used as this method have the ability to minimize the sum of squares of the residual errors, which make the approximate solution become more accurate and converge to the exact solution. This study will provide an insight into minimizing and controlling the formation of tension on subsea cable and assist in the establishment of numerical approach of minimization without gradient-based technique.

1.4 Research Objectives

The objectives of this study are:

i. To formulate two-dimensional mathematical model related to tension analysis of subsea cable in steady state condition for the case of subsea cable with and without buoyancy module.
ii. To solve the two-dimensional subsea cable problem related to tension analysis of the subsea cable by using numerical approach of minimization without gradient-based technique.
iii. To determine the suitable subsea cable configuration with buoyancy module for deployment near to platform area.

1.5 Scope of the Research

The scope of this study is as follows:

i. This study considers the formulation of two-dimensional subsea cable problem related to the tension analysis of the subsea cable in steady state condition for the case of subsea cable with and without buoyancy module.

ii. This study only involves mathematical formulation and the simulation of subsea cable tension without and with buoyancy module in which the simulation will be focused on getting the suitable cable configuration in condition of shallow water near the platform area considering the depth to be 80m.

iii. In this study, only one type of numerical approach of minimization technique is considered when solving the tension analysis of subsea cable which is minimization without gradient-based technique.

1.6 Significance of the Research

In particular, the deployment of subsea cable in shallow water will cause much more complexity as compared to deep water because the current velocity in shallow water has much greater significance in the structural performance of the subsea cable. Thus, subsea cable configuration is one of the key points that must be considered during the design process of the whole operation in order to enhance the structural performance of the subsea cable especially near to the platform area. More accurate amount of cable tension can improve the subsea cable lifetime and directly minimize the cost of the whole cable deployment by avoiding any formation of slack. The outcomes of the present study will help to clearly understand the behavior and the mechanics of subsea cables while providing an insight into choosing suitable cable configuration in certain condition.

The new formulated model in this study is basically aimed to mitigate the negative impacts that might reduce the subsea cable lifetime and maintenance. Thus, this study will eventually provide a numerical simulation on minimizing subsea cable tension with the consideration of two types of configuration for future reference: (1) subsea cable without buoyancy module; (2) subsea cable with buoyancy module. The new mathematical model is formulated by considering different boundary condition approach with some special treatment based on the physical and mechanical laws of subsea cable. The tension analysis of subsea cable is obtained by considering the use of numerical approach of minimization without gradient-based technique as this method would provide more accurate approximate solution to the related problem and its ability in solving problem with some more complex geometry. It is also important to note that the application of numerical approach of minimization without gradient-based technique on subsea cable problem can be very useful as it can minimize sum of squares of the residual errors produced during the calculation of the solution to the related problem which will provide more accurate solution.

Next, MATLAB program codes for cable tension analysis is developed based on minimization without gradient-based technique in order to conveniently check the performance of numerical methods in subsea cable problem. The MATLAB program is utilized in this study due to its ability and availability of the optimization toolbox which can be used for the calculation purpose in this study. The formulation of MATLAB algorithm with the available built-in library for minimization problem provide a shorter time in obtaining the approximate solution compared to the classical discretization technique which requires more complex command on solving the problem. In order to get the physical understanding of the related problem, the solutions and finding are plotted. This enable the results to be clearly presented and comparison can be made between each simulation of subsea cable without and with buoyancy module.

1.7 Thesis Organization

This thesis is divided into five chapters. The first chapter provides a brief introduction to this research. This chapter consists of research background, problem statement, scope of the study and significance of the study.

In Chapter 2, some basic knowledge related to this research is presented by looking back through past study. The basic knowledge included in this chapter are some historical background of subsea cable, subsea cable laying concept and mathematical model related to subsea cable problem. Explanation of the mathematical optimization method as well as its application are reviewed. Limitation and research gap for this study are also discussed in this chapter.

Chapter 3 begins by formulating the mathematical model related to subsea cable tension for the case without buoyancy module. The boundary condition formulated based on the physical and mechanical laws of subsea cable are explained in detail in this chapter. After that, the mathematical model is extended by considering the use of buoyancy module on certain part of subsea cable. The result of the subsea cable tension analysis for both cases are discussed in Chapter 4.

The summary of the whole thesis is provided in Chapter 5. Some recommendations for further research related to this topic are also given in this chapter. A flowchart of thesis organization is given in Figure 1.1 to explain the whole body of thesis.

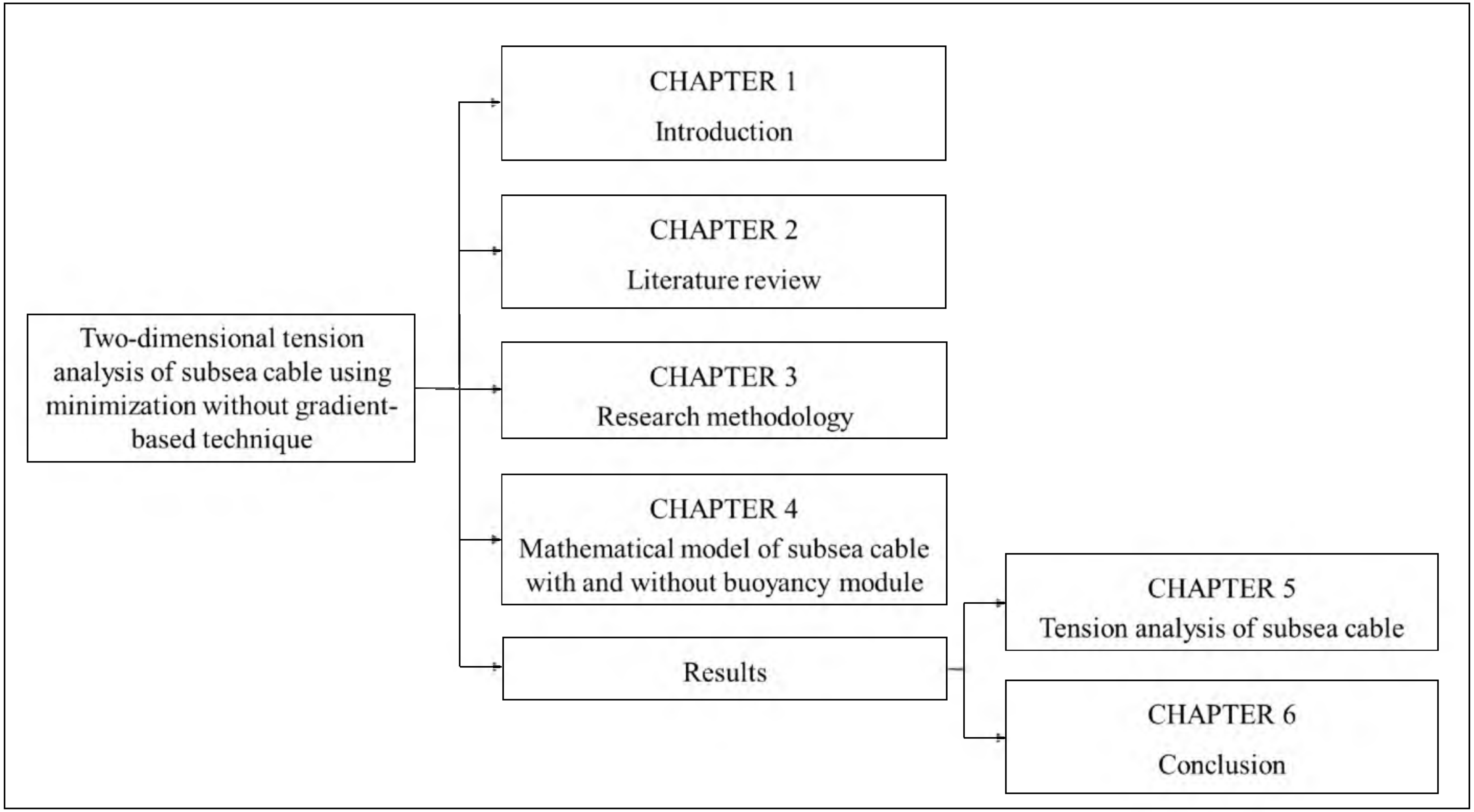

Figure 1.1 Thesis organization.

REFERENCES

Abidin, A. R. Z., Mustafa, S., Aziz, Z. A., & Ismail, K. (2018). Subsea Cable Łaying Problem. *MATEMATIKA: Malaysian Journal of Industrial and Applied Mathematics, 34*(2), 173-186.

Bai, Y. (2014). *Analysis of Subsea Buried Pipelines and Partially Buried Cables.* (Doctor of Philosophy), Texas A&M University

Belegundu, A. D., & Arora, J. S. (1985). A study of mathematical programming methods for structural optimization. Part I: Theory. *International Journal for Numerical Methods in Engineering, 21*(9), 1583-1599.

Bellman, R. (1954). The theory of dynamic programming. *Bulletin of the American Mathematical Society, 60*(6), 503-515.

Brent, R. P. (1973). *Algorithms for minimization without derivatives*. Englewood Cliffs: Prentice Hall.

Burgess, J. (1991) Modelling of undersea cable installation with a finite difference method. *Proceedings of the First (1991) Interational Offshore and Polar Engineering Conference*. 11-16 August. Edinburgh, United Kingdom, 222-227.

Chucheepsakul, S., Srinil, N., & Petchpeart, P. (2003). A variational approach for three-dimensional model of extensible marine cables with specified top tension. *Applied Mathematical Modelling, 27*(10), 781-803.

De Zoysa, A. P. (1978). Steady-state analysis of undersea cables. *Ocean Engineering, 5*(3), 209-223.

Drąg, Ł. (2016). Application of dynamic optimisation to the trajectory of a cable-suspended load. *Nonlinear Dynamics, 84*(3), 1637-1653.

Drąg, Ł. (2017). Application of dynamic optimisation to stabilise bending moments and top tension forces in risers. *Nonlinear Dynamics, 88*(3), 2225-2239.

Dreyer, T., & Van Vuuren, J. H. (1999). A comparison between continuous and discrete modelling of cables with bending stiffness. *Applied Mathematical Modelling, 23*(7), 527-541.

Fiacco, A. V., & McCormick, G. P. (1968). *Nonlinear programming: sequential unconstrained minimization techniques.* (Vol. 4). United States of America: Society for Industrial and Applied Mathematics.

Fogel, D. B. (1994). An introduction to simulated evolutionary optimization. *IEEE transactions on neural networks, 5*(1), 3-14.

Fouchard, G. (2016). *Historical overview of submarine communication systems*, in Chesnoy, J. *Undersea Fiber Communication Systems*. Academic Press: Elsevier, 21-52.

Friswell, M. I. (1995). Steady-state analysis of underwater cables. *Journal of waterway, port, coastal, and ocean engineering, 121*(2), 98-104.

Gao, Q., Duan, M., Liu, X., Wang, Y., Jia, X., An, C., & Zhang, T. (2018). Damage assessment for submarine photoelectric composite cable under anchor impact. *Applied Ocean Research, 73*, 42-58.

Han, H., Li, X., & Zhou, H.-S. (2018). 3D mathematical model and numerical simulation for laying marine cable along prescribed trajectory on seabed. *Applied Mathematical Modelling, 60*, 94-111.

Howison, S. (2005). *Practical Applied Mathematics: Modelling, Analysis, Approximation.* United Kingdom: Cambridge University Press.

Jasman, N. A., Normisyidi, N. A. L., Hoe, Y. S., Abidin, A. R. Z., & Haniffah, M. R. M. (2019). Numerical Calculation of Two-Dimensional Subsea Cable Tension Problem Using Minimization Approach. *MATEMATIKA: Malaysian Journal of Industrial and Applied Mathematics, 35*(4), 15-32.

Jia, X., Gao, Q., Wang, L., Duan, M., & Zhang, T. (2015). Field test research on failure of photoelectric composite submarine cable under impaction by dropped anchors. *The 2015 World Congress on Advances In Structural Engineering and Mechanics*. 25-29 August. Incheon, Korea, 4-10.

Kojima, N., Yabuta, T., Negishi, Y., Iwabuchi, K., Kawata, O., Yamashita, K.,Yoshizawa, N. (1982). Submarine optical fiber cable: Development and laying results. *Applied optics, 21*(5), 815-821.

Kuhn, H., & Tucker, A. (1951). *Nonlinear Programming,* in Giorgi, G., & Kjeldsen, T. H. (2013) *Traces and emergence of nonlinear programming*. Springer Science & Business Media, 247-258.

Masciola, M. D., Nahon, M., & Driscoll, F. R. (2011). Static analysis of the lumped mass cable model using a shooting algorithm. *Journal of waterway, port, coastal, and ocean engineering, 138*(2), 164-171.

Mondal, R. (2014). Dynamic analysis of marine cable. *International Journal of Scientific & Engineering Research, 5*(3), 769.

Nocedal, J., & Wright, S. J. (1999). Numerical optimization, P. Glynn and SM Robinson, eds. In: Springer.

Osiński, M., & Wojciech, S. (1998). Application of nonlinear optimisation methods to input shaping of the hoist drive of an off-shore crane. *Nonlinear Dynamics, 17*(4), 369-386.

Park, H., Jung, D., & Koterayama, W. (2003). A numerical and experimental study on dynamics of a towed low tension cable. *Applied Ocean Research, 25*(5), 289-299.

Patel, M., & Vaz, M. (1995). The transient behaviour of marine cables being laid—the two-dimensional problem. *Applied Ocean Research, 17*(4), 245-258.

Rao, S. S. (2009). *Engineering optimization: theory and practice*: John Wiley & Sons.

Rosenbrock, H. (1960). An automatic method for finding the greatest or least value of a function. *The Computer Journal, 3*(3), 175-184.

Russenschuck, S. (1999). *Mathematical Optimization Techniques*. Paper presented at First International Roxie Users Meeting and Workshop. 16-18 March. Switzerland, 60-72.

Simoncelli, E. (1999). Least squares optimization. *Center for Neural Science, and Courant Institute of Mathematical Sciences.* Retrieved Sepember 25, 2019, from https://www.cns.nyu.edu.

Taormina, B., Bald, J., Want, A., Thouzeau, G., Lejart, M., Desroy, N., & Carlier, A. (2018). A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions. *Renewable and Sustainable Energy Reviews, 96*, 380-391.

Vaz, M., & Patel, M. (2000). Three-dimensional behaviour of elastic marine cables in sheared currents. *Applied Ocean Research, 22*(1), 45-53.

Vaz, M., Witz, J., & Patel, M. (1997). Three dimensional transient analysis of the installation of marine cables. *Acta mechanica, 124*(1-4), 1-26.

Ventikos, N., & Stavrou, D. (2013). Submarine power cables: laying procedure, the fleet and reliability analysis. *Journal of Marine Engineering & Technology, 12*(1), 13-26.

Wang, C., Cheong, H., & Chucheepsakul, S. (1993). Static analysis of marine cables via shooting-optimization technique. *Journal of waterway, port, coastal, and ocean engineering, 119*(4), 450-457.

Wang, F., Huang, G.-l., & Deng, D.-h. (2008). Steady state analysis of towed marine cables. *Journal of Shanghai Jiaotong University (Science), 13*(2), 239.

Wang, J., & Duan, M. (2015). A nonlinear model for deepwater steel lazy-wave riser configuration with ocean current and internal flow. *Ocean Engineering, 94*, 155-162.

Wang, J., Duan, M., Fan, J., & Liu, Y. (2013). *Static equilibrium configuration of deepwater steel lazy-wave riser*. Paper presented at the The Twenty-third International Offshore and Polar Engineering Conference.

Wang, J., Duan, M., & Luo, J. (2015). Mathematical model of steel lazy-wave riser abandonment and recovery in deepwater. *Marine Structures, 41*, 127-153.

Wang, Y., Bian, X., Zhang, X., & Xie, W. (2010). *A study on the influence of cable tension on the movement of cable laying ship.* Paper presented at the OCEANS 2010 MTS/IEEE SEATTLE.

Wrench, G. (2000). *The History of Submarine Telecommunication Cables*. Paper presented at the Man-Made Objects on the Seafloor 2000. 2-3 May. London, United Kingdom, 71-79.

Xiang, X., Yu, C., Niu, Z., & Zhang, Q. (2016). Subsea Cable Tracking by Autonomous Underwater Vehicle with Magnetic Sensing Guidance. *Sensors, 16*, 1335.

Yang, N., & Jeng, D.-S. (2014). *Three-dimensional Analysis of Elastic Marine Cable during Laying.* Paper presented at the The Eleventh ISOPE Pacific/Asia Offshore Mechanics Symposium.

Yang, N., Jeng, D., & Zhou, X. (2013). Tension analysis of submarine cables during laying operations. *Open Civ. Eng. J, 7*(1), 282-291.

Yincan, Y., Xinmin, J., Guofu, P., & Wei, J. (2018). Submarine Optical Cable Engineering: Elsevier Science.

Yoshizawa, N., & Yabuta, T. (1983). Study on submarine cable tension during laying. *IEEE journal of oceanic engineering, 8*(4), 293-299.

Zajac, E. (1957). Dynamics and kinematics of the laying and recovery of submarine cable. *The Bell System Technical Journal, 36*(5), 1129-1207.

Zhang, Z.-g., Ding, Z.-g., Dong, Y.-j., Yuan, Z.-l., Tao, H.-c., & Wang, J.-j. (2018). The Study of Burial Depth and Risk Assessment of Submarine Power Cable. *4th International Conference on Green Materials and Environmental Engineering (GMEE2018)*. 28-29 October. Beijing, China.

Zoutendijk, G. (1960). *Methods of feasible directions: a study in linear and non-linear programming*: The University of California: Elsevier Publishing Company.

LIST OF PUBLICATION

Non-indexed Journal

1. **Jasman, N. A.**, Normisyidi, N. A. L., Hoe, Y. S., Abidin, A. R. Z., and Haniffah, M. R. M. (2019). Numerical Calculation of Two-Dimensional Subsea Cable Tension Problem Using Minimization Approach. *MATEMATIKA: Malaysian Journal of Industrial and Applied Mathematics, 35*(4), 15-32.

Book Chapter

1. **Jasman, N. A.**, Normisyidi, N. A. L., Hoe, Y. S., and Haniffah, M. R. M Modelling and Simulation of Subsea Cable with Buoyancy Module. In: UTM-CIAM. *Mathematics Matters in Malaysian Industries.* Accepted.