Optimal Control for Ocean Wave Energy Converters

Ragnar Lothbrok

13th October 2022
Version: First Draft

Optimal Control for Ocean Wave Energy Converters

by

Ragnar Lothbrok

A dissertation submitted to

The University of She□eld

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

13th October 2022

Ragnar Lothbrok

Optimal Control for Ocean Wave Energy Converters

PhD Dissertation, 13th October 2022

Supervisors: Dr Super Nice Guy
Dr Grumpy Guy

The University of She□eld

Department of Automatic Control and Systems Engineering

Amy Johnson Building

Portobello Street

Sheffield, S1 3JD

The real man smiles in trouble, gathers strength from distress, and grows brave by reflection

Proud Odin's Son

To the ferocious shield-maiden battlefields have had:

Lagertha.

Acknowledgement

To my family for their unconditional love and support.

Declaration

I, Ragnar Lothbrok, declare that the work presented in this thesis is my own. All material in this thesis which is not of my own work, has been properly accredited and referenced.

Sheffield, 13th October 2022

Ragnar Lothbrok

Abstract

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Contents

1

Intro

> There is no wealth but life. Life, including all its powers of love, of joy, and of admiration.
>
> – **John Ruskin** –

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1.1. Intro - Section 1

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1.2. Intro - Section 2

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1.2.1 Intro - Section 2.1

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1.2.2 Intro - Section 2.2

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1.3. Research Aim

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1.4. Research Objectives

The project's overarching aim will be accomplished through the following list of objectives:

a) Objective 1

b) Objective 2

c) Objective 3

d) Objective 4

1.5. Research Contributions

The prime contributions gathered throughout the development of this project are summarised below:

a) The primary contribution of the project is the development and implementation of...

b) A further contribution is the proposal and implementation of ....

c) Contribution of the paper -

d) Contribution of the paper .

e) Finally, a parallel contribution of this project is...

1.6. Dissertation Outline

This dissertation is presented as...

- Chapter 1: Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

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- Chapter 4: Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

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2

Dissertation Background

> A genius is the man who can do the average thing when everyone else around him is losing his mind.
>
> – **Napoleon** –

2.1. Ch2 - Section 1

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2.2. Ch2 - Section 2

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Figure 2.1.: Classification of wave energy converters by site of deployment. Extracted from [5]

2.3. Ch2 - Section 3

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Figure 2.2.: Schematic representation of oscillating column water devices and overtopping devices. Extracted from [12]

2.3.1 Ch2 - Subsection 3.1

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2.3.2 Ch2 - Subsection 3.2

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Figure 2.3.: Examples of wave activated body devices with its respective classification based on the orientation. Extracted from [13]

Applying the Newtons 2nd law to the floater, the motion of a point absorber WEC can be described in general by the following equation:

$$\text{"} \; \text{¥}_{1\text{C}^{\text{o}}} = {}_{1\text{C}^{\text{o}}} \; , \; {}_{6}{}_{1\text{C}^{\text{o}}} \; , \; {}_{?\text{C}>1\text{C}^{\text{o}}} \; , \; {}_{4\text{GC}} \tag{2.1}$$

where " is the inertial matrix, is the displacement of the floater, relative to its hydrostatic equilibrium position, is the hydrodynamic force, $_6$ is the gravity force, $_{\%)\,\$\,1\text{C}^{\text{o}}}$ is the force exerted by the power take-off system (described in section XXX, control input), and $_{4\text{GC}}$ group all possible external forces. This latter may include, but not limited to, mooring and other potentially non-linear forces, for example, end-stop forces.

2.4. Chapter Summary

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3

Control Strategies: State of the Art

> The world is full of obvious things which nobody by any chance ever observes.
>
> – **Sherlock Holmes** –

3.1. Ch3 - Section 1

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Table 3.1.:Comparison of the main characteristics of single wave energy converters studies review

Reference	Dynamic Model		Constraints					Rad. Term	Excitation Force	Objective Function					Optimisation Problem			Robust Control
	LTI	N-L	Amp.	vel.	u	u	Pow.			Ene.	u	U	Svar	Tt	Q-P	N-LP	IN-met	
Model Predictive Control Strategies																		
[14]	X		X		X			Not considered	Predicted	X							X	
[15]	X		X	X	X			Damping	Perfect prediction	X		X	X		X			
[16]		X	X	X	X			Damping	Ideal Prediction	X		X	X			X		
[17]	X		X		X	X		Damping	Predicted	X	X	X			X			
[18]	X		X	X	X			Implicit	Perfect knowledge	X	X				X			
[19]	X				X			Implicit	Predicted	X	X				X			
[20]		X	X	X	X			Not considered	Predicted	X		X	X			X		
[21]	X				X		X	ss-4th order	Perfect knowledge	X		X					X	
[22]	X				X			Not speci ed	Predicted	X		X			X			
[23]	X				X			ss - 5th order	Predicted	X	X					X		
[24]	Experimental application of [23]																	
[25]	X		X	X		X		Damping	Predicted					X	X			
[26]	X		X			X		ss - 4th order	Ideal Prediction					X	X			
[27]	X		X	X	X			ss - 4th order	Perfect knowledge	X		X			X	X		
Hals2011	X		X		X			ss - 4th order	Ideal Prediction						X			
[28]	X		X					ss - 6th order	Perfect knowledge	X	X				X			
[29]	X		X	X				ss - 5th order	Perfect knowledge	X	X	X			X			
[30]	X		X		X			ss - 5th order	Predicted	X		X			X			
[31]	X		X	X	X			Not speci ed	Predicted	X					X			
[32]	X				X			Not speci ed	Not speci ed	X					X			
[33]	X				X			ss - 4th order	Not speci ed					X	X			
[34]	X			X				ss - 3rd order	Perfect knowledge	X							X	
Model Predictive Ccontrol - Like Strategies																		
[35]		X	X		X			ss - 3rd order	Predicted	X						X		
[36]	X		X					SP (Fourier)	Predicted	X						X		
[37]	X		X	X	X			PS (HRCF)	Not speci ed	X						X		
[38]	X		X		X			Damping	Not speci ed	X		X				X		
[39]		X	X	X	X		X	PS (Fourier)	Not speci ed	X						X		
[40]	X		X		X			ss - 8th order	Perfect knowledge	X						X		
[41]	X		X		X			SP/PS (Fourier)	Not speci ed	X					X	X		
[42]		X						PS (Fourier)	Not speci ed	X						X		
[43]	X		X	X	X			PS (HRCF)	Perfect knowledge	X						X		
[44]	X		X	X	X			PS (HRCF)	Perfect knowledge	X						X		
[45]	X		X	X	X			PS (Fourier)	Not speci ed	X					X			
[46]	X		X	X	X			PS (HRCF)	Not speci ed	X					X			

Note: This table is based partially on the information published in [47].

3.2. Ch3 - Section 2

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Figure 3.1.:Classi cation of wave energy converters by site of deployment. Extracted from [5]

3.3. Ch3 - Section 3

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Figure 3.2.: Schematic representation of oscillating column water devices and overtopping devices. Extracted from [12]

3.3.1 Ch3 - Subsection 3.1

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3.3.2 Ch3 - Subsection 3.2

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Applying the Newtons2=3 law to the oater, the motion of a point absorber WEC can be described in general by the following equation:

$$" \; ¥1Ć = \; ^1Ć \; , \; \; _6{}^1Ć \; , \; \; ?C\gtrless^1Ć \; , \; \; _{4GC} \qquad (3.1)$$

where " is the inertial matrix, is the displacement of the oater, relative to its hydrostatic equilibrium position, is the hydrodynamic force, $_6$ is the gravity force, $_{\%)\$}{}^1Ć$ is the force exerted by the power take-o system (described in section XXX, control input), and $_{4GC}$group all possible external forces. This latter may include, but not limited to, mooring and other potentially non-linear forces, for example, end-stop forces.

Figure 3.3.: Examples of wave activated body devices with its respective classi cation based on the orientation. Extracted from [13]

3.4. Chapter Summary

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4

Contributions

> You can't do better design with a computer, but you can speed up your work enormously.
>
> Wim Crouwel –

4.1. Ch4 - Section 1

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4.2. Ch4 - Section 2

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Figure 4.1.:Classi cation of wave energy converters by site of deployment. Extracted from [5]

4.3. Ch4 - Section 3

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Figure 4.2.: Schematic representation of oscillating column water devices and overtopping devices. Extracted from [12]

4.3.1 Ch4 - Subsection 3.1

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4.3.2 Ch4 - Subsection 3.2

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Figure 4.3.: Examples of wave activated body devices with its respective classi cation based on the orientation. Extracted from [13]

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where " is the inertial matrix, is the displacement of the oater, relative to its hydrostatic equilibrium position, is the hydrodynamic force, $_6$ is the gravity force, $_{\%)\$}{}^1Ć$ is the force exerted by the power take-o system (described in section XXX, control input), and $_4GC$ group all possible external forces. This latter may include, but not limited to, mooring and other potentially non-linear forces, for example, end-stop forces.

4.4. Chapter Summary

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5

Conclusions and future work

> Anyone who stops learning is old, whether at twenty or eighty. Anyone who keeps learning stays young. The greatest thing in life is to keep your mind young.
>
> Henry Ford –

5.1. Conclusions

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5.2. Future work

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Appendices

A

Paper 1

Paper 1

Paper 1

Paper 1

Paper 1

Paper 1

B

Paper 2

Paper 2

Paper 2

Paper 2

Paper 2

Paper 2

C

Paper 3

Paper 3

Paper 3

Paper 3

Paper 3

Paper 3