DEPARTMENT OF ENGINEERING CYBERNETICS

Multivariable SES control

with linearly mixed control signals

Håvard A. Storvold

Supervised by
Jan Tommy Gravdahl
Øyvind F. Auestad

Fall 2018

Summary

In this project report a control system for a surface effect ship will be developed. The system uses the vent valves releasing air from the air cushion to control the vessels sway, yaw and heave motion. It includes modelling the dynamics of the vessel, especially in regards to cushion forces. For the control side it implements PID controllers and a purpose made linear mixing system with special considerations made for input limitations. Simulation results from different sea states are presented and analysed with comparisons to a set of baseline simulations.

Preface

For the last few decades a large portion of the development of new surface effect ships has been centred in Norway, in large part at UMOE Mandal. UMOE has, because of this, collaborated with NTNU to create projects for master students to complete as a part of their degree. This report was written as a part of a masters degree at the Department of Engineering Cybernetics and was completed in the span from August to December 2018. I would like to thank my supervisors, Professor Jan Tommy Gravdahl at NTNU and Dr. Øyvind F. Auestad at UMOE Mandal for their help, and UMOE for sharing some of their modelling data on surface effect ships.

Table of Contents

Summary **i**

Preface **ii**

Table of Contents **iv**

List of Figures **v**

Abbreviations **vi**

1 Introduction **1**

2 Basic Theory **3**
2.1 Dynamic equation 3
2.2 Cushion forces 4
2.2.1 Pressure forces 4
2.2.2 Thrust forces 4

3 Control **7**
3.1 Linear controllers 7
3.1.1 Sway vent valve control 7
3.1.2 Yaw vent valve control 8
3.1.3 Heave vent valve control 8
3.2 Saturation and mixing 8
3.3 Sensitivity control 9

4 Simulations **11**
4.1 Simulation scenarios 11
4.2 Baseline 12
4.2.1 Scenario 1 12
4.2.2 Scenario 2 12
4.2.3 Scenario 3 13

4.3 Equal priorities . . . 13
4.3.1 Scenario 1 . . . 13
4.3.2 Scenario 2 . . . 14
4.3.3 Scenario 3 . . . 14
4.4 Ignore heave . . . 14
4.4.1 Scenario 2 . . . 15
4.4.2 Scenario 3 . . . 15
4.5 Prioritise sway . . . 16
4.5.1 Scenario 2 . . . 16
4.5.2 Scenario 3 . . . 16
4.6 Prioritise heave . . . 17
4.6.1 Scenario 2 . . . 17
4.7 Ignore sway . . . 17
4.7.1 Scenario 2 . . . 17
4.7.2 Scenario 3 . . . 18

5 Analysis **19**
5.1 Baseline . . . 19
5.2 Equal priority . . . 19
5.2.1 Scenario 1 . . . 19
5.2.2 Scenario 2 . . . 19
5.2.3 Scenario 3 . . . 20
5.3 Priority manipulation . . . 20
5.3.1 Ignore heave . . . 20
5.3.2 Prioritise sway . . . 20
5.3.3 Prioritise heave . . . 20
5.3.4 Ignore sway . . . 20
5.4 Input saturation . . . 21

6 Conclusion **23**
6.1 Physical feasibility . . . 23
6.2 Linear mixing system . . . 23
6.3 Further work . . . 23

Bibliography **25**

Appendix **27**

List of Figures

4.1 Three separate simulations with no waves present 12
4.2 Three separate simulations with 2 meter waves 12
4.3 Three separate simulations with 2.5 meter waves 13
4.4 Simulation with no waves 13
4.5 Simulation with 2 meter waves 14
4.6 Simulation with 2.5 meter waves 14
4.7 Simulation with 2 meter waves and no heave compensation 15
4.8 Simulation with 2.5 meter waves and no heave compensation 15
4.9 Simulation with 2 meter waves and prioritised sway control 16
4.10 Simulation with 2.5 meter waves and prioritised sway control 16
4.11 Simulation with 2 meter waves and prioritised heave compensation 17
4.12 Simulation with 2 meter waves and no sway control 17
4.13 Simulation with 2.5 meter waves and no sway control 18

6.1 Input values for simulation with 2.5 meter waves, only sway control . . . 27
6.2 Input values for simulation with 2.5 meter waves, equal priorities 28
6.3 Input values for simulation with 2.5 meter waves, no sway control 28

Abbreviations

SES	=	Surface Effect Ship
ACV	=	Air Cushion Vehicle
BCS	=	Boarding Control System
RCS	=	Ride Control System
CG	=	Center of gravity
CC	=	Center of air cushion
vv	=	Vent valve
PID	=	Proportional, integrating and derivative controller

Chapter 1

Introduction

The surface effect ship arrived as an alternative to the concept of an air cushion vehicle, commonly known as the ”hovercraft”. It offers less air leakage, better stability and the ability to use water propulsion system at the cost of amphibious abilities. The SES works by sealing an air cushion in between its two water piercing sidehulls, this air is kept in by fore and aft seals. The air pressure in the air cushion is typically 2 to 5% higher than ambient pressure, maintained by lift fans and vent valves.

In the 1960s the UK was developing SES ferries while the U.S. Navy was the driving force behind development of larger surface effect warships Clark (2011), but eventually discarded the concept. Today the main military user of surface effect ships is the Royal Norwegian Navy, operating minehunters, minesweepers and corvettes. The corvettes, named the Skjold-class, being among the fastest combat warships in the world. The other military users being Russia, with two missile corvettes, and Sweden with a stealth torpedo boat, now used as a training platform.

A core element of SES operation is to use the vent valves and lift fans to maintain proper ride height and cushion pressure. This system was originally intended to keep pressure constant, but investigations into reducing wave frequency movement in heave was conducted by (Kaplan (1981)), and expanded again to combat acoustic effects by (Sørensen (1995)). An adaptive wave cancellation scheme was proposed by (Basturk H. (2011)) and further work in developing wave cancellation schemes with full scale tests has been done by (Butler (1985)). Some of these models include contact with another ship or a platform and are often referred to as boarding control systems.

Most of these earlier systems use symmetrical vent valve openings, as this is optimal for controlling the cushion pressure. More recent work such as Bua and Vamråk (2016) and Bryn and Tønnesen (2011) look at using asymmetrical vent valve openings to utilise the thrust forces produced by escaping air. In this project a method for using differential vent valve opening on a ship with four lateral vent valves to control the sway and yaw movement of the ship will be developed. This will work alongside the existing controllers to improve motion control of the vessel in both stationary and transit conditions. The signals will be mixed according to both input saturation and user priorities.

Chapter 2

Basic Theory

2.1 Dynamic equation

In order to create a simulation environment a model of the ship at sea had to be developed. This was done by simplifying and modifying the general marine system model (Fossen (2011)),

$$M\dot{\nu} + C(\nu, \nu_r) + D(\nu_r, \mu) + g(\eta) = \tau_{env} + \tau_{ctrl}$$

into the model used for the simulation,

$$M\dot{\nu} + B_\nu \nu_r + B_{\nu 2}\nu_r|\nu_r| + \mu + g(\eta) = \tau_{env} - \tau_{cush} \tag{2.1}$$

The coordinate system used to describe the body frame in this report is defined as follows: Origin in centre of gravity, x-axis in the forward direction of the vessel, z-axis downwards, and y-axis toward starboard to complete the right hand system.

Symbol	**Formula**	**Description**
η	$\dot{\eta} = J_b^n(\theta_{nb})\nu$	Position $\eta = [n, e, d, \theta, \phi, \psi]$ NED-frame
ν	-	Velocity in body frame
ν_c	-	Velocity of the water current
ν_r	$\nu - \nu_c$	Velocity relative to the current
μ	$\dot{\mu} = A_m\mu + B_m\nu_r$	Fluid memory variable
M	$= M_{RB} + M_A$	Total mass, vessel + added
B_ν	-	Linear viscous damping
$B_{\nu 2}$	-	Quadratic viscous damping
$g(\eta)$	-	Gravity and buoyancy

Table 2.1: Table of symbols

2.2 Cushion forces

For this section the forces from the cushion's pressure and the thrust forces from the escaping air will be looked at separately, as $\tau_{cush(P)}$ and $\tau_{cush(T)}$ respectively. This gives:

$$\tau_{cush} = \tau_{cush(P)} + \tau_{cush(T)} \tag{2.2}$$

2.2.1 Pressure forces

The air cushion can be seen as a uniformly pressurised chamber where the bottom surface is the waters surface. Assuming the water level is close to equal along the cushion edges and the cushion is symmetric across the CG x-y-plane, the horizontal forces will be negligible. This leaves:

$$\tau_{cush(P)} = \begin{bmatrix} 0 \\ 0 \\ -A_c \Delta p_u \\ 0 \\ A_c \Delta p_u (x_{CC}) \\ 0 \end{bmatrix} \tag{2.3}$$

where A_c is the effective area of the air cushion in the xy-plane and p_u is the uniform pressure of the cushion. Note that in the simulation $x_{CC} = 0$, and the cushion does not induce any pitching torque.

2.2.2 Thrust forces

For the type of SES in question all the vent-valves exhaust along the crafts y-axis giving no forces toward heave or surge. The thrust from a single vent-valve can be calculated by the momentum of the air leaving the valve, $F_{thrust} = \frac{d}{dt} p_a ir = \dot{m} v_{air} = \rho_{air} Q_{out}$. Here p_{air} is the momentum of the air leaving the vent, v_{air} its velocity, and m its mass. Q_{air} it the volume of air flowing out through the duct, and ρ_{air} its density the expansion of the air due to reduction in pressure is ignored. Assuming equal airflow through the duct area, and that the duct area is the same as the maximum vent area, A_{Lmax}, v_{air} can be calculated as

$$v_{air} = \frac{Q_{out}}{A_{Lmax}}$$

$$F_{thrust} = \frac{\rho_{air}}{A_{Lmax}} Q_{out}^2 \tag{2.4}$$

where Q_{out} can be approximated as

$$Q_{out} = c_n A_L(t) \sqrt{\frac{2p_u(t)}{\rho_{air}}}$$

where $A_L(t)$ is the active vent area, i.e. not being restricted by a valve, and c_n being a loss coefficient. This gives

$$F_{thrust} = \frac{2c_n^2}{A_{Lmax}} A_L^2(t) p_u$$

with $A_L(t)$ assumed a linear function of the commanded value vv_{cmd}.
Let the thrust from valve number $i = 1, 2, ..., n$ be denoted $F_{thrust}(i)$ and its position be $x_{vv}(i)$ and $y_{vv}(i)$. Assuming that all vent valves point along the y-axis outward from the centerline of the ship, allows for expressing the direction of the thrust as a function of the position in unit vector form as

$$\begin{bmatrix} 0 \\ sign(y_{vv}(i) \end{bmatrix}$$

this results in thrust cushion forces:

$$\tau_{cush(T)} = \begin{bmatrix} 0 \\ \sum_{i=1}^{n} -F_{thrust}(i) sign(y_{vv}(i)) \\ 0 \\ 0 \\ 0 \\ \sum_{i=1}^{n} F_{thrust}(i) x_{vv}(i) sign(y_{vv}(i)) \end{bmatrix} \tag{2.5}$$

Combining equations 2.3 and 2.5 in equation 2.2 gives:

$$\tau_{cush} = \begin{bmatrix} 0 \\ \sum_{i=1}^{n} -F_{thrust}(i) sign(y_{vv}(i)) \\ -A_c \Delta p_u \\ 0 \\ A_c \Delta p_u (x_{CC}) \\ \sum_{i=1}^{n} -F_{thrust}(i) x_{vv}(i) sign(y_{vv}(i)) \end{bmatrix} \tag{2.6}$$

Chapter 3

Control

3.1 Linear controllers

For sway and yaw control simple PID controllers were implemented, where ϵ_{sway} and ϵ_{yaw} are the errors along their respective axis. The variables u_{sway} and u_{yaw} represent a generalised force that would stabilise the low frequency movement along the two axis. For the purpose of the control loops, low frequency include anything significantly lower than the frequency of the waves. Because of this, LPF() represents a first order low pass filter that has a cutoff frequency significantly lower than the frequency of the expected waves.

$$u_{sway} = K_{ps}LPF(\epsilon_{sway}) + K_{is}\int_0^t \epsilon_{sway}dt + K_{ds}LPF(\dot{\epsilon}_{sway})$$

$$u_{yaw} = K_{py}LPF(\epsilon_{yaw}) + K_{iy}\int_0^t \epsilon_{yaw}dt + K_{dy}LPF(\dot{\epsilon}_{yaw})$$

These synthetic inputs will be converted into vent valve commands, called vv_{cmd}, a vector composed of individual control signals, $[vv_{cmd}(1) \quad vv_{cmd}(2) \quad ... \quad vv_{cmd}(n)]^T$, where i is the corresponding vent valve number using strictly linear functions

3.1.1 Sway vent valve control

As discussed in section 2.2.2, the direction of the force in body frame can be represented in unit vector form as:

$$\begin{bmatrix} 0 \\ sign(y_{vv}(i) \end{bmatrix}$$

Considering the second element of the vector in equation 2.6, it can be seen that in order to generate thrust along the sway axis, or body y-axis it is desirable to create a difference if thrust between the vent valves on either side of the ships centerline. This is equivalent to linearizing the second element of the vector in equation 2.6, about $F_{thrust}(i)$ for

$F_{thrust}(i) = u_{sway}$. This can be implemented by, for each vent valve, multiplying the control signal u_{sway} with the valves position, i.e:

$$vv_{sway} = \begin{bmatrix} vv_{sway}(1) \\ vv_{sway}(2) \\ ... \\ vv_{sway}(n) \end{bmatrix} \tag{3.1}$$

$$vv_{sway}(i) = -u_{sway} sign(y_{vv}(i)) \tag{3.2}$$

3.1.2 Yaw vent valve control

Similarly to what was done with the sway control, to convert u_{yaw} into vent valve commands that generate torque a linearization of equation 2.6 can be used. This yields the following controller

$$vv_{yaw} = \begin{bmatrix} vv_{yaw}(1) \\ vv_{yaw}(2) \\ ... \\ vv_{yaw}(n) \end{bmatrix} \tag{3.3}$$

$$vv_{yaw}(i) = u_{yaw} x_{vv} sign(y_{vv}(i)) \tag{3.4}$$

Because these vent valve commands are applied inversely symmetrical about the y-axis, this does not produce a horizontal force.

3.1.3 Heave vent valve control

In order to control the heave motion of the craft we use an existing BCS, boarding control system, described in an article by Auestad (2015). The output from this controller u_{BCS} will be applied equally to all vent valves and thus will not give any net force towards sway nor yaw:

$$vv_{BCS} = \begin{bmatrix} vv_{BCS}(1) \\ vv_{BCS}(2) \\ ... \\ vv_{BCS}(n) \end{bmatrix} \tag{3.5}$$

$$vv_{BCS}(i) = u_{BCS} \tag{3.6}$$

3.2 Saturation and mixing

In order to implement the control signals presented in equations 3.2, 3.4, and 3.6, which all are designed to set all n vent valve commands on their own, they need to be combined in some way.

$$vv_{cmd} = f(vv_{sway}, vv_{yaw}, vv_{BCS}) \tag{3.7}$$

One such function commonly used in multirotor systems would be a simple sum. This would, in our system, be expressed as:

$$vv_{cmd} = vv_{sway} + vv_{yaw} + vv_{BCS}$$

This relies on the assumption that the craft does not operate near its upper nor lower input limits, but during early simulations it was found that this is not the case. As each individual controller could saturate the system even in mild seas. The vent valve commands are allowed to vary between zero and vv_{max} and are designed to average around a value called vv_{bias} that will result in an average cushion pressure that maintains the intended ride height. This information directs us to an improved version of the sum-based control input mixer:

$$vv_{cmd} = \frac{vv_{sway} + vv_{yaw} + vv_{BCS}}{C_{scaling}} + vv_{bias} \tag{3.8}$$

where $C_{scaling}$ varies in order to keep the signals within saturation limits. This can be implemented as:

$$C_{scaling} = \frac{g(vv_{sway} + vv_{yaw} + vv_{BCS}, \alpha)}{\alpha} \tag{3.9}$$

where $\alpha = min(vv_{max} - vv_{bias}, vv_{bias})$ and $g(v, \alpha)$, for a vector v with elements v_1 to v_n, is defined as
$g(v) = max(|v_1|, |v_2|, ..., |v_n|, \alpha)$, where the inclusion of $vv_{max} - vv_{bias}$ is to ensure that $C_{scaling}$ can never be less than 1, and can thus never amplify any of the controllers. This is important in order to protect the stability properties of the individual controllers.

3.3 Sensitivity control

As the system stands it can mix our controllers within the given limits. However the user has no control over how much of the available actuation that is dedicated to each controller at a given time. In this section a system for normalising and prioritising the errors will be proposed. This will be done using a symmetrical saturation function and a priority vector P:

$$sat(x, a) = \begin{cases} a & : x \geq a \\ x & : -a \leq x \leq a \\ -a & : x \leq -a \end{cases}$$

$$P = [P_{sway}, P_{BCS}, P_{yaw}] \tag{3.10}$$

For a vector x with i elements, $sat_{vec}(x, a)$ will be a function such that

$$sat_{vec}(x, a) = \begin{bmatrix} sat(x_1, a) \\ sat(x_2, a) \\ ... \\ sat(x_i, a) \end{bmatrix}$$

Using these functions we can rewrite equation 3.8 to be

$$vv_{cmd} = \frac{\sum^{controllers} (P_{controller} vv_{controller})}{C_{scaling}} \tag{3.11}$$

Where $C_{scaling}$ is now defined as

$$C_{scaling} = \frac{g(P_{sway} vv_{sway} + P_{yaw} vv_{yaw} + P_{BCS} vv_{BCS}, \alpha)}{\alpha} \tag{3.12}$$

With α and $g(v, \alpha)$ as before.

Chapter 4

Simulations

The simulations for this report were implemented using MATLAB Simulink and solved using the built-in ode45 solver. It used a variable step size algorithm with a maximum step size of 0.1 seconds. The model and its parameters are loosely based on the Wavecraft series by UMOE Mandal, but does not represent any specific craft. It has been based on both theoretical and experimental values, courtesy of UMOE Mandal, and uses the MSS toolbox library by Fossen and Perez (2004).

4.1 Simulation scenarios

The simulations in this chapter will all be variations on a scenario in which the vessel does a simultaneous step response in both sway and yaw, in the simulations where waves are present they will travel normally to the ships initial heading. The wave height and amplitude will be set according to the following table for each of the three scenarios and will be generated using the MSS toolbox.

Scenario	Wave height(peak to peak)	Period	Sea state	Typical wind speed
1	0	-	0	0
2	2 m	8 s	4	8-12 m/s
3	2.5 m	10 s	4-5	12-15 m/s

The wave height frequency, and typical wind speed combinations are approximate values following deep water theory for fully developed sea. These types of waves are meant to represent offshore conditions. Sea state classification is a code used by the World Meteorological Organisation to roughly describe average wave height.

4.2 Baseline

To create a baseline for the properties of each controller, the system was simulated with each individual controller separately, with the other controllers disabled. Each of the following plots show three separate simulations, where only the state associated with the active controller is shown.

4.2.1 Scenario 1

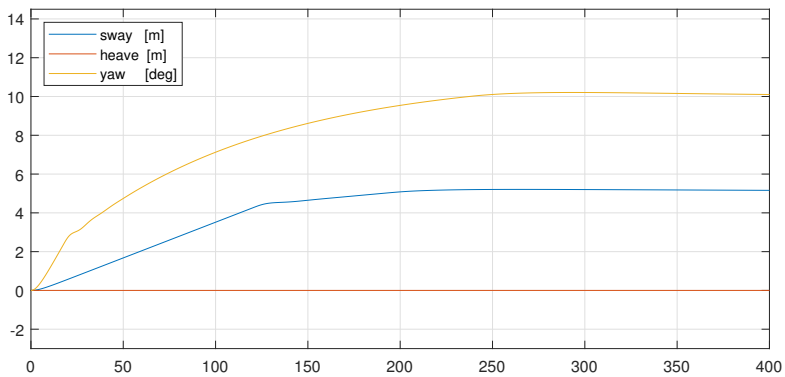

Figure 4.1: Three separate simulations with no waves present

4.2.2 Scenario 2

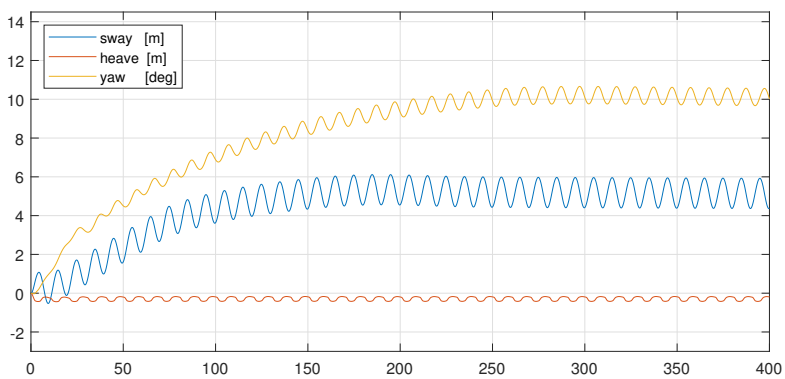

Figure 4.2: Three separate simulations with 2 meter waves

4.2.3 Scenario 3

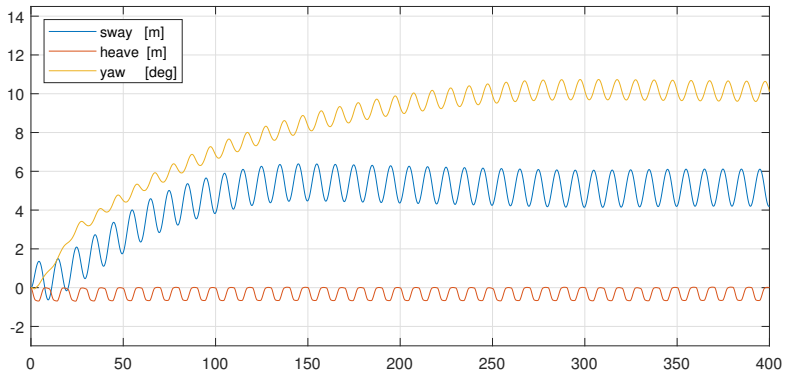

Figure 4.3: Three separate simulations with 2.5 meter waves

4.3 Equal priorities

To test the mixing algorithm the three controllers were run simultaneously and with equal priority on their outputs. Unlike in the previous section, the following plots present three states in the same simulation run.

4.3.1 Scenario 1

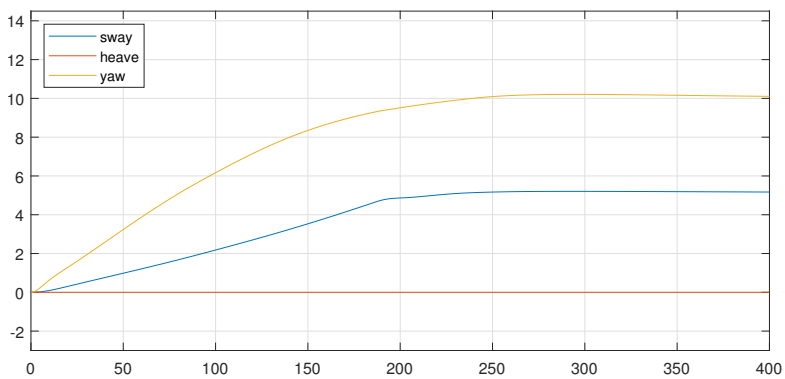

Figure 4.4: Simulation with no waves

4.3.2 Scenario 2

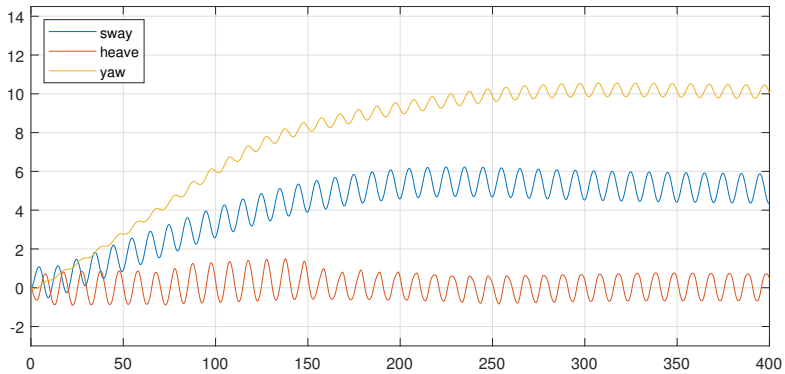

Figure 4.5: Simulation with 2 meter waves

4.3.3 Scenario 3

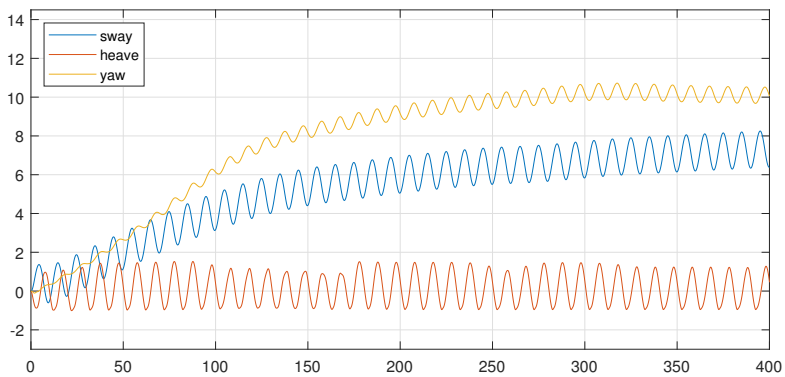

Figure 4.6: Simulation with 2.5 meter waves

4.4 Ignore heave

In order to tune the system for different scenarios the user is given access to the three priority values discussed in section 3.3. One possible use for this is to disable one controller in the hope that this improves the functionality of the other two. By setting the values to

$P = [101]$, which as seen in equation 3.10 disables the BCS, simulations with only sway and yaw compensation were ran.

4.4.1 Scenario 2

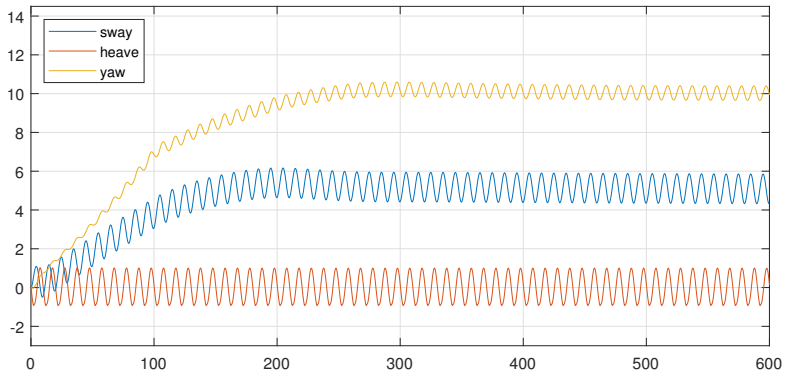

Figure 4.7: Simulation with 2 meter waves and no heave compensation

4.4.2 Scenario 3

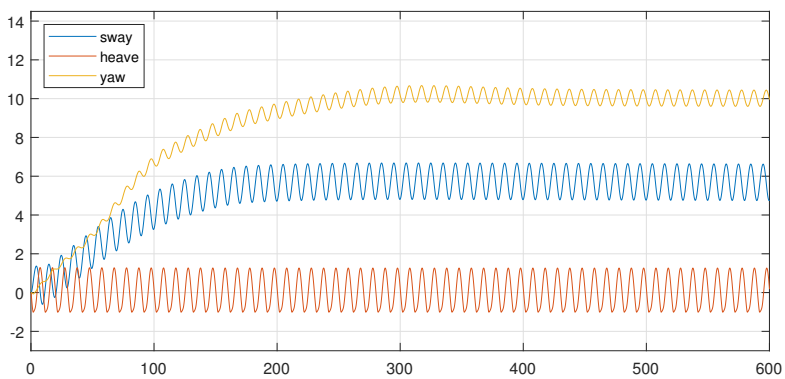

Figure 4.8: Simulation with 2.5 meter waves and no heave compensation

4.5 Prioritise sway

Another use for the priority values is to lower the effect of one controller, to make sure that controller does not severely reduce the performance of the others, but still have it preform some of its function when possible. By setting the values to $P = [10.250.4]$ for the second scenario, or $P = [10.150.4]$ for the third, as defined in equation 3.10, sway is now prioritized.

4.5.1 Scenario 2

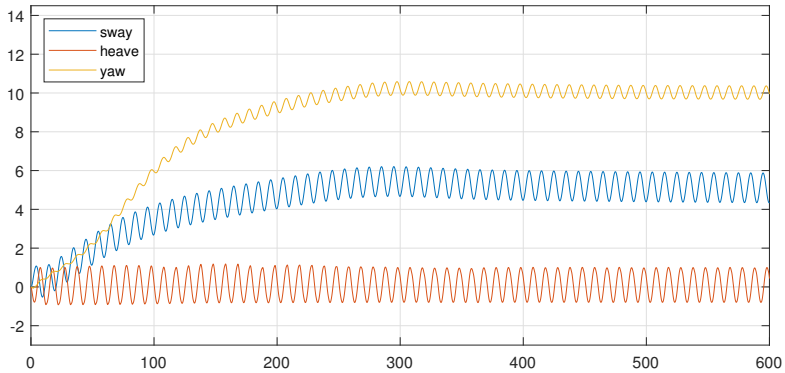

Figure 4.9: Simulation with 2 meter waves and prioritised sway control

4.5.2 Scenario 3

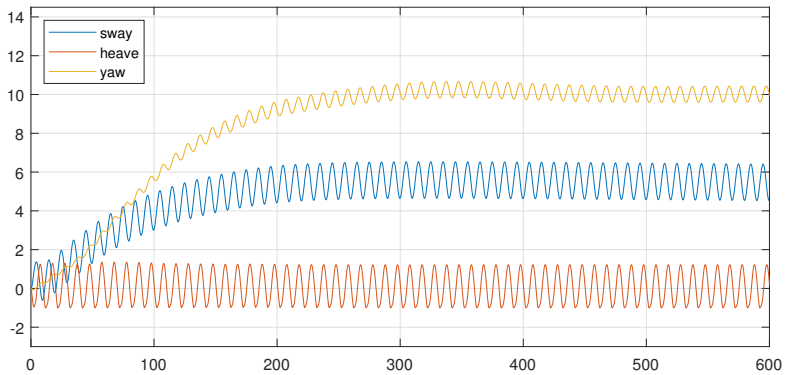

Figure 4.10: Simulation with 2.5 meter waves and prioritised sway control

4.6 Prioritise heave

Should the user want to dampen the motion of the ship due to waves, he might want to prioritise the heave motion as the other controllers have negligent impact on motions of that frequency.

4.6.1 Scenario 2

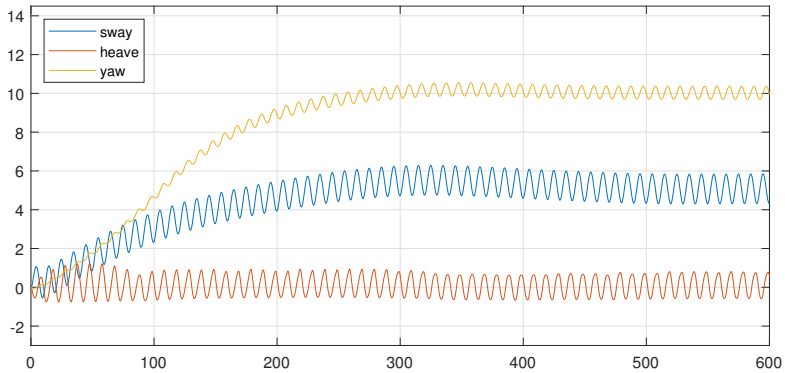

Figure 4.11: Simulation with 2 meter waves and prioritised heave compensation

4.7 Ignore sway

4.7.1 Scenario 2

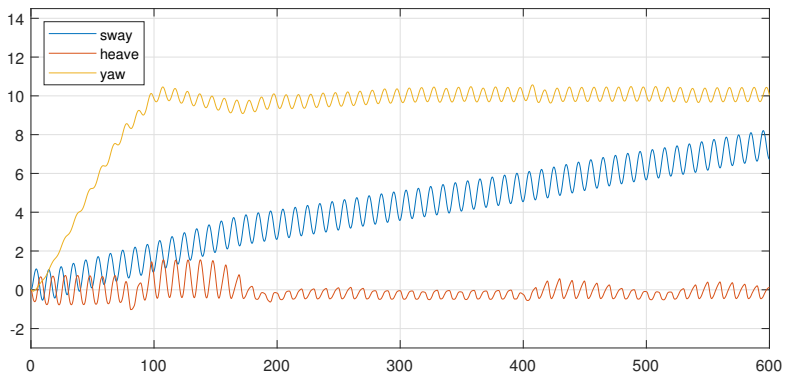

Figure 4.12: Simulation with 2 meter waves and no sway control

4.7.2 Scenario 3

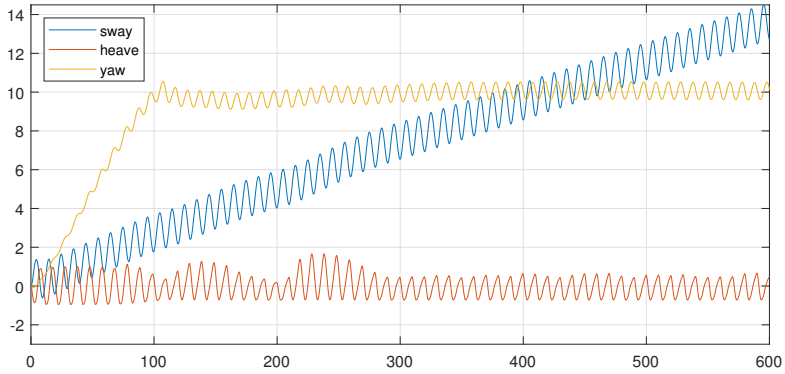

Figure 4.13: Simulation with 2.5 meter waves and no sway control

Chapter 5

Analysis

This section will take a look at the results from the previous section in order to qualitatively describe their performance.

5.1 Baseline

From the results in section 4.2 it is clear that the controllers can stabilise their associated state in the case when the controllers operate alone. It is clear that the sway and yaw motions eventually oscillate about their set-points of 5m and 10° respectively. For the heave controller, we confirm that is can reduce the amplitude of the motion to well below the amplitude of waves passing the craft.

5.2 Equal priority

These were the first results we got from the three controllers working together. When all the priority signals are equal, one may expect to see the performance degraded by equal portions for all the controllers.

5.2.1 Scenario 1

With no waves present the controllers perform close to how fast they performed when operating independently. It should be noted that the BSC, or heave controller, produces control inputs near zero when no waves are present. This results in only two controllers ”sharing” the available vent valve control range.

5.2.2 Scenario 2

With the 2m waves, measured peak-to-peak i.e. 1m amplitude, the convergence rate of the sway axis seems almost unaffected, however the yaw axis converges notably slower. What

becomes apparent when looking at the heave motion, is that its performance is severely degraded when there are large errors in the other two states, but regains a lot of its functionality when they converge, eventually reducing the heave motion by almost half.

5.2.3 Scenario 3

This scenario is closer to the limit for what the actuators can do in terms of sway movement, from the figures in section 4.3.3, we can see that the actuators are not able to maintain a stable position, resulting in an unbounded error. This constant, but not quite enough, input from the sway controller results in the BCS not managing a major reduction in heave motion amplitude.

5.3 Priority manipulation

In order to change the operation of the controllers for different scenarios the user is meant to be able the change the priority values. In sections 4.4 to 4.6 in the previous chapter some possible combinations that were theorised to improve the performance for that specific scenario were tested.

5.3.1 Ignore heave

When there is no heave compensation the other controllers the other controllers improve their performance drastically. This is especially obvious is figure 4.8, where the sway motion is no longer unbounded, but still does not oscillate about zero.

5.3.2 Prioritise sway

Next there was an attempt to lower both the heave and the yaw priorities to stabilise the sway motion. This resulted in similar results as ignoring heave entirely when there was 2.5m waves, but for the scenario where there was only 2 meter waves the heave compensation managed to reduce heave motion by approximately 20%.

5.3.3 Prioritise heave

For the case where heave compensation is deemed by the user to be more important, the priority for both sway and yaw were reduced and heave compensation had a greater effect compared to when equal priorities were applied. It can also be seen than the BCS starts yielding noticeable damping while there is still some error on the other two axis.

5.3.4 Ignore sway

When the sway controller was disabled in its entirety the convergence rate of the yaw controller and the amount of dampening in heave were drastically increased.

5.4 Input saturation

For the simulations in figures 4.1(only sway control), 4.6 and 4.13, plots of the inputs in vv_{cmd} can be found in the appendix as figures 6.1, 6.2 and 6.3 respectively. From equation 3.2 the sway controller creates a difference between port and starboard vent valve openings, and comparing figures 6.2 and 6.3 the effect of the constant sway control input needed to combat the drift caused by the waves become obvious.

Chapter 6

Conclusion

6.1 Physical feasibility

For a ship that resembles the simulated one control of sway, heave and yaw using the air cushion vent valves is definitely possible given calm to moderate seas. One of the major obstacles the system encountered were the constant push given by the waves coming in towards the ship. It should also be possible to combine this with the water-jet thrust system from the main propulsion to eliminate some of the slowest variations.

6.2 Linear mixing system

The linear mixing system was functional in its base operation, but when the system operated near its physical limitation it became clear that the mixing system was far from optimal. It produced unbounded errors when it could have been avoided and did not allow for a moving vv_{bias} to utilise more of the available inputs.

6.3 Further work

One of the ways the system could improve its functionality is with the use of wave filtering as a preferable option to low pass filtering. It could also prove useful to control the system according to an earth fixed trajectory or path, allowing for additional use cases. One could also try to incorporate the water-jet thrust into the system to allow for more control axis and/or current compensation.

Bibliography

Auestad, Ø. F., G. J. T. e. a., 2015. Boarding control system for improved accessibility to offshore windturbines: Full-scale testing. Control Engineering Practice 45.

Basturk H., e. a., 2011. Air cushion adaptive disturbance cancellation for the reduction of wave induced motion of ramp-connected ships. 11th International Conference on Fast Sea Transportation (FAST) 2011.

Bryn, H. E., Tønnesen, J., 2011. The quest for speed at sea. CARDEROCK DIVISION, NSWC — TECHNICAL DIGEST.

Bua, N. H., Vamråk, V. M., 2016. Sway control on a surface effect ship. NTNU Departement of Marine Technology Master Thesis.

Butler, E. A., 1985. The surface effect ship. Naval Engineers Journal, 200–253.

Clark, Dennis J., e. a., 2011. The quest for speed at sea. CARDEROCK DIVISION, NSWC — TECHNICAL DIGEST.

Fossen, T., 2011. Handbook of Marine Craft Hydrodynamics and Motion Control. John Wiley & Sons.

Fossen, T. I., Perez, T., 2004. Marine Systems Simulator (MSS). `URL:https://github.com/cybergalactic/MSS`, [Online; accessed Aug 2018].

Kaplan, P., 1981. Dynamics and hydrodynamics of surface-effect ships. SNAME Vol 89, 211–247.

Sørensen, A. J., 1995. Design of ride control system for surface effect ships using dissipative control. Automatica Vol 31, 183–199.

Appendix

Selected input plots

Baseline sway control 2.5m waves

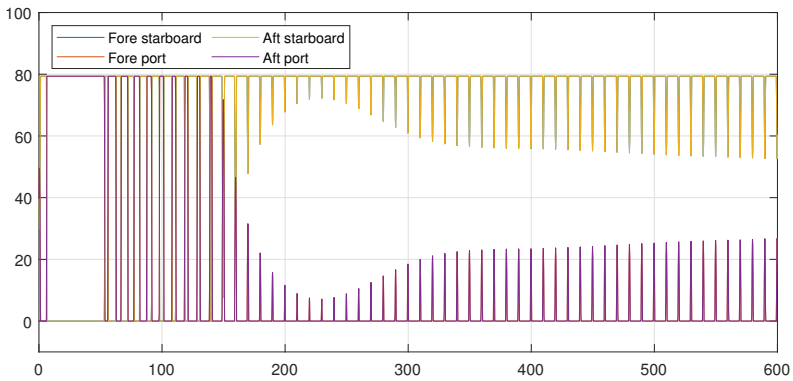

Figure 6.1: Input values for simulation with 2.5 meter waves, only sway control

Equal priorities 2.5m waves

Ignored sway control 2.5m waves

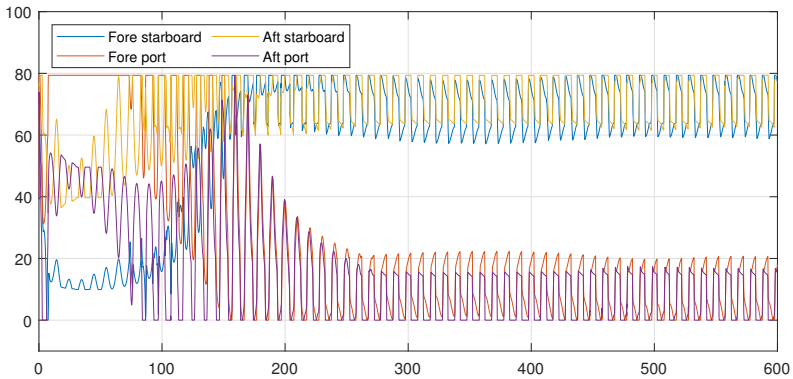

Figure 6.2: Input values for simulation with 2.5 meter waves, equal priorities

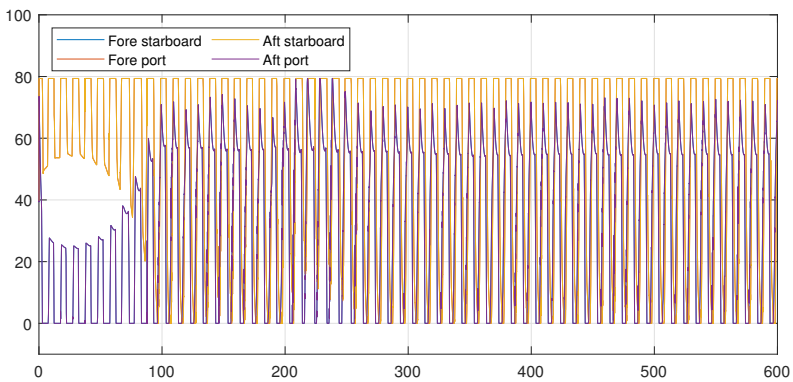

Figure 6.3: Input values for simulation with 2.5 meter waves, no sway control