AALBORG UNIVERSITY
STUDENT REPORT

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STUDENT REPORT

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Preface

This report was made by three students from Aalborg University Esbjerg attending the 4th semester of the Electronics and Computer Engineering course. From this point on, every mention of **we**, **the group** or **the authors** refers to the three co-authors listed below.

All resources produced for this project can be found on the GitHub repository [**GitHub**]. Selected resources are also in the appendix.

Aalborg University, October 1, 2018

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Contents

Acronyms & Nomenclature

Symbol	**Definition**	**Unit**
H	Head	*bar*
MFM	Magnetic Flow Meter	
MIMO	Multiple Input Multiple Output	
ML	MATLAB®	
NPSH	Net Positive Suction Head	*bar*
OL	Open-loop	
OS	Operating System	
P	Power	W
PC	Personal Computer	
QDM	Quarter Decay Method	
SISO	Single Input Single Output	
SL	Simulink®	
SLRT	Simulink® Real-Time™	
USM	Ultimate Sensitivity Method	
ΔP	Pressure difference	*bar*
η	Efficiency	%
ρ	Density	$\frac{kg}{m^3}$
ω	Rotational speed	$\frac{rad}{s}$

	Subscripts
cl	Controller
el	Electric
hyd	Hydraulic
ref	Reference
tot	Total

	Prescripts
Δ	Change

Chapter 1

Introduction

Reading Guide

Chapter 2

Problem Description

2.1 Problem Description

2.2 Control Methods

2.3 Problem Delimitation

2.3.1 Requirements

Chapter 3

Mathematical Modelling

3.1 Static Modelling

Single Pump Model

$$H = \bar{a_2} \cdot Q^2 + \bar{a_1} \cdot Q + \bar{a_0} \tag{3.1}$$

$$P = \bar{b_3} \cdot Q^3 + \bar{b_2} \cdot Q^2 + \bar{b_1} \cdot Q + \bar{b_0} \tag{3.2}$$

$$\left(\frac{\omega_1}{\omega_2}\right)^1 = \frac{Q_1}{Q_2} \qquad \left(\frac{\omega_1}{\omega_2}\right)^2 = \frac{H_1}{H_2} \qquad \left(\frac{\omega_1}{\omega_2}\right)^3 = \frac{P_1}{P_2}$$

[Volk2014].

$$H(\omega) = a_0 \cdot \omega^2 + a_1 \cdot \omega \cdot Q(\omega) + a_2 \cdot Q(\omega)^2 \tag{3.3}$$

$$P(\omega) = b_0 \cdot \omega^3 + b_1 \cdot \omega^2 \cdot Q(\omega) + b_2 \cdot \omega \cdot Q(\omega)^2 + b_3 \cdot Q(\omega)^3 \tag{3.4}$$

$$a_0 = \frac{\bar{a_0}}{\bar{\omega_0^2}} \qquad a_1 = \frac{\bar{a_1}}{\bar{\omega_0}} \qquad a_2 = \bar{a_2}$$

$$b_0 = \frac{\bar{b_0}}{\bar{\omega_0^3}} \qquad b_1 = \frac{\bar{b_1}}{\bar{\omega_0^2}} \qquad b_2 = \frac{\bar{b_2}}{\omega_0} \qquad b_3 = \bar{b_3}$$

[Yang2010]

$$a_0 = -0.03044 \qquad a_1 = 0.07635 \qquad a_2 = 1.688$$

$$b_0 = -0.2825 \qquad b_1 = -0.7147 \qquad b_2 = 54.39 \qquad b_3 = 163.7$$

3.2 Dynamic Modelling

$$\frac{Y(s)}{U(s)} = \frac{A \cdot e^{-st_d}}{\tau \cdot s + 1} \tag{3.5}$$

- A = final value the step response settles at
- t_d = time delay
- τ = time it takes from 0.1 of final value to 0.9 final value

Chapter 4

Model Validation

4.1 Static Modelling

$$H(\omega) = \frac{\bar{a_0}}{\bar{\omega_0^2}} \cdot \omega^2 + \frac{\bar{a_1}}{\bar{\omega_0}} \cdot \omega \cdot Q(\omega) + \bar{a_2} \cdot Q(\omega)^2 \tag{4.1}$$

$$P(\omega) = \frac{\bar{b_0}}{\bar{\omega_0^3}} \cdot \omega^3 + \frac{\bar{b_1}}{\bar{\omega_0^2}} \cdot \omega^2 \cdot Q(\omega) + \frac{\bar{b_2}}{\omega_0} \cdot \omega \cdot Q(\omega)^2 + b_3 \cdot Q(\omega)^3 \tag{4.2}$$

4.2 Dynamic Modelling

Chapter 5

Discussion

In this chapter we discuss the initially stated requirements and compare them with the results achieved. We will also have a look at future work opportunities, to be done on top of this project.
This chapter will also explain the process of working on this project.

We initially set out three primary goals for this project:

- Creation of a dynamic model for one pump
- Design of a PID controller for the flow
- Tuning of said PID controller

And three secondary goals:

- Creation of a static model for one pump
- Creation of a static model for multiple pumps
- Design of a controller for the flow, taking efficiency into account

Looking back at the project, we can now say that all primary goals and some of the secondary goals were met.
We created a dynamic model for a single pump through analysis of experimental data and assuming a transfer function of the form $\frac{Y(s)}{U(s)} = \frac{Ae^{st_d}}{\tau s+1}$. Where all coefficients were found analysing a step response. This model gave a good fit to our step response data, but didn't perform perfectly to test the actual controller.

The design and tuning of the PID controller was primarily done on the physical setup, instead of the simulation, because it was readily accessible and provided good results. This is also the reason for the dynamic model not being our first priority when it came to time management.

We initially set out to describe the whole system, with all three pumps as a MIMO system and be able to control the total flow with minimal power consumption. This was to be achieved by using multiple pumps and benefiting from the shifted maximum efficiency point as stated in previous research. When we realised that we would not be able to finish that project in the given timeframe, we chose to implement a PID control on a SISO system instead. The knowledge gained about the system from developing the static model was helpful to determine an operating range for the PID control. It showed that almost identical dynamics were to be expected at all points $0\% < CV_1 \leq 100\%$ and $10\% \leq \omega P \leq 100\%$. It also evens the path for future work on energy efficiency, because there already exists a reliable model of the power consumption with respect to H and Q, which can easily be extended to a model of the efficiency.

- Maximum Overshoot $M_p = 0\%$
- Steady-state error $e_{ss} \leq 1\%$

With the manually tuned PID controller, all requirements set in 2.3.1 and shown above were hit, but this was done by making the system very slow and creating a very big delay in reaction.

With more intensive tuning and more reasonable requirements, better coefficients for a PID controller could possibly be found. Specifically requiring no overshoot is not expected to be reasonable in most applications of a flow controller. It might for example be more beneficial to require the integral of the error to be very small, to ensure steady flow on average.

5.1 Future Work

As with every project, not all work on this topic is done yet. We therefore propose a small list of future work opportunities. Some of the points on that list are inspired by our initial goal, energy efficiency.

Development of a more robust dynamic model. As stated in Section 3.2, our dynamic model was not a perfect description of the system. With more advanced modelling techniques and more research into this, a better model could be found. This would benefit most other future work.

While developing our static model, we found that it was not accurate for the whole operating range of the system. We believe it is possible to find a model better suited, if more work is put into this topic. This would also benefit most other future work and maybe also the general understanding of pumping systems.

Research in the industry to find what requirements actually matter should be conducted, to ensure that the next iteration of this controller would be useful.

Based on our research alone, we cannot know which factors to prioritise and therefore not build a beneficial controller.

Our initial goal of efficiency optimisation was not met, due to a shift in focus. We still think this is a worthwhile goal to work on. Since we already put some thought into the topic, we propose building a decisive logic to decide how many pumps to use, which might be possible to implement as a lookup table. A more reliable approach would of course be modelling the efficiency of 1, 2 and 3 pumps according to Q and H and developing a MIMO controller taking those factors into account. Developing a reliable model for the efficiency could help building a lookup table or decisive logic to switch between multiple pumps.

Chapter 6

Conclusion

From the Problem Delimitation in Chapter 2 there were three primary goals for this project.

A dynamic model was created according to a very simple transfer function. All variables were gathered through a step response test. This helped achieve a dynamic model very similar to the system response throughout the whole operating range.

The development of a static model through polynomial fitting helped understand the pumps capabilities and set a reasonable setpoint for controller testing. It also made it possible to get an idea of the power consumption and will help in future work towards efficiency optimisation.

All stated requirements were hit, even though we conclude they might not fit to real world requirements.

As stated in Section 5.1 possible future work could be aiming towards energy efficiency. Some steps required in that direction would be better modelling and more complex control. The final goal for a better controller could be maintaining a set flow at maximal efficiency, by using optimal scheduling of multiple pumps in parallel.