Thesis Proposal - Scania Gearbox Oil Conditioning Controller

Chieh-Ju Wu and Charles Brinkley

January 10, 2022

Acronyms

ARMA autogregressive moving average model. 9

ARMAX autoregressive moving average with extra input model. 9

ARX autoregressive with extra input model. 9

BJ Box-Jenkins model. 9

FPE final prediction error. 10

LQR linear quadratic regulator. 8

MIMO multiple-input multiple-output. 8

NLR Powertrain Test Rig Development. 3

NLRI Testing Systems. 2, 3, 7

NRME normalized root mean square). 10

PI proportional-integral. 3

PLC programmable logic controller. 6

SISO single-input single-output. 6

TSK Takagi Sugeno Kang. 10

1 Introduction

To validate various gearbox designs, Scania's Testing Systems (NLRI) subgroup uses dynamometer testbeds to simulate various load cycles on their gearboxes. As part of this endeavour, it is desired to maintain a specific oil temperature throughout testing by means of a closed loop heat exchanger system. Customers (i.e. other engineering departments within Scania) give little to no notice before requiring testing and fast results. Therefore, tuning of the temperature controller has to be done quickly and guided mainly by intuition. This thesis proposes a possible method to quickly derive an improved plant model by means of data-driven modelling. Then, with this improved plant model, this thesis also explores a possible controller design method that may improve transient response and stability while respecting the time constraints of this scenario; a proportional-integral (PI) controller designed with pole placement (with the help of this new model) rather than manual tuning.

2 Background

Scania AB is a world leading producer of heavy lorries, trucks and buses, but also manufactures powertrain components for general industrial applications as well [1]. They have been historically known for their diesel engine technology, but have more recently been investing heavily into more sustainable solutions such as hybrid and electrical technologies. To test these new developments, the Powertrain Test Rig Development (NLR) group, and more specificially the NLRI subgroup, manages a plethora of different testbeds between their three major locations around the world. Each are configured for specific types of testing and networked together on network for continuous monitoring from anywhere.

For this particular thesis, the testbed in question focuses on testing of different gearboxes in development; those mated to internal combustion, electric, and hybrid motors. To conduct these tests, a large dynamometer is mated to the gearbox being tested. A dynamometer is a device that simultaneously measures torque and angular velocity of a rotating object. Two major dynamometer types exist; one that applies a small load to measure power output of the test object (*power absorption* types) and another where power is transmitted from the dynamometer itself, measured, and then used to do work on the test object (*power transmission* or *motoring* types) [2]. Within these two categories exist many mechanical approaches. In this particular case, an electric power transmission dynamometer is used to apply different loads on the gearbox that simulate various driving conditions. The testing being done varies widely depending on what the customer is hoping to study.

The loading of the gears, bearings, and clutches create surface wear, so oil is cycled through the gearbox housing via an internal pump (dependent on gearbox speed) to continually protect these components and transfer the generated heat. This oil differs between gearboxes, but each has a specific operating temperature range to prevent any type of failure. To ensure this temperature remains nominal during testing, an external fluid-to-fluid heat exchanger is used. This system incorporates individually closed-loop refrigerant and heater cycles that maintains a water-glycol fluid at a constant temperature, flow rate, and pressure. A 3-way valve then regulates the ratio of hot and cold fluid that is ultimately fed to the main shell-and-tube heat exchanger connected to the gearbox's oiling system [3]. A simplified diagram of the gear box oil conditioning system can be seen in figure 1 below. The flow rate and temperature of the gearbox oil changes based on the load and rotational speed, so a controller must be used to actuate this 3-way valve and ultimately regulate the gearbox oil temperature.

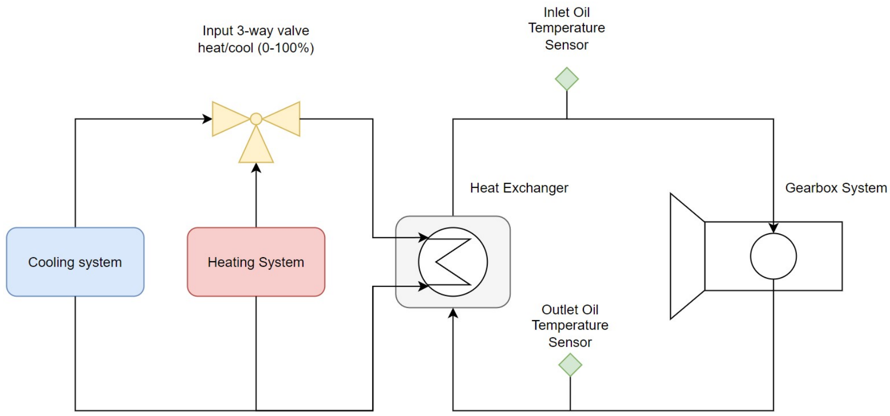

Figure 1: A simplified version of the gearbox oil conditioning system

To model this heat exchanger plant, Scania currently utilizes a block diagram that was developed in LabVIEW (a graphical programming environment) using some known system physics as well as manual tuning by observation [4]. It has been acknowledged that this is not accurate enough to verify controller parameters. A better study on the physics of the system could produce a more accurate model, but this non-linear system of such complexity and unknown noise/disturbances was deemed too time consuming to model further. The system is known to be non-linear based on the main working principle of this type of heat exchanger (see equations 2.1-2.3 below corresponding to figure 2)[5]. Testing is also usually requested at a moments notice and results are expected in only a few days. The plant model changes with each test setup, so spending the resources to develop such a model is not very advantageous.

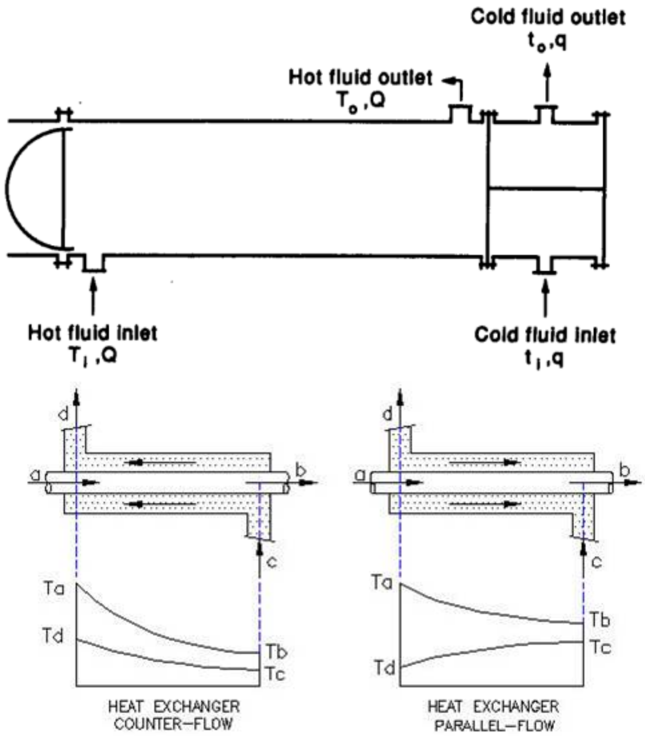

Figure 2: Diagram of a shell-and-tube heat exchanger with working dynamic principle [5]

$$T_o = \frac{(2ab - a + b)T_i}{(2ab + a + b)} + \frac{(2a)t_i}{2ab + a + b} \tag{2.1}$$

$$a = \frac{q\rho C_c}{UA} \tag{2.2}$$

$$b = \frac{Q\rho C_c}{UA} \tag{2.3}$$

Where...

$$A = \text{Overall heat transfer area}$$
$$C_c = \text{Specific heat of cold fluid}$$
$$Q = \text{Volumetric flow rate of gearbox oil (varying)}$$
$$q = \text{Volumetric flow rate of cold fluid (constant)}$$
$$T_i = \text{Inlet Temperature of hot fluid (gearbox oil)}$$
$$t_i = \text{Inlet temperature of cold fluid (water-glycol)}$$
$$T_o = \text{Outlet temperature of hot fluid}$$
$$t_o = \text{Outlet temperature of cold fluid}$$
$$U = \text{Overall heat transfer coefficient}$$
$$\rho = \text{Cold fluid density}$$

This approach to plant modelling (where the thermodynamics and fluid physics are known) is called *physical* or *white-box* plant modelling [6]. In cases where the exact physics of the system are not known, derived models are considered *black-box* or *grey-box* (where some basic model structure is known). The act of deriving an implicit mathematical expression of a physical system based on test data is known as *data-driven modelling.* Data-driven modelling is a broad topic with many approaches depending on the system in question, but in general, the process consists of taking input-output data of a dynamic system, defining assumptions, utilizing various statistical and/or machine learning techniques to develop a transfer function, polynomial expression, or a neural network, then validated using additional experimental data [7].

Due to the short time provided for testing and the inaccuracy of their plant model, viable controller options are limited. Therefore, only a basic PI output feedback controller is implemented. The closed loop system is of a single-input single-output (SISO) where oil temperature, either at the inlet or exit of the gearbox (depending on customer needs), is read and the resulting error to the reference is transformed with the controller to a valve position input (0-100 %). The controller parameters are manually tuned by observation and intuition during testing.

The controller for this heat exchanger system is implemented with a programmable logic controller (PLC) and Scania is currently migrating all testbeds to use Beckhoff's TwinCAT 3 ecosystem and their Controller Toolbox specifically [8]. A PLC is a specific type of computer commonly used for automation in harsh industrial environments where safety, robustness, and real-time execution is required. The benefit of TwinCAT is the comparatively larger list of viable communication protocols, the fact that it supports C/C++ as well as conventional PLC lanugages (structured text and instruction lists), support for a variety of third party software integrations, and many graphical tools that make creating and maintaining projects a simple task.

3 Motivation

One of the main responsibilities of the NLRI group is to test their customers' gearbox systems performance during various loading cycles. Predefined input signals for the dynamometer are provided by their customers to evaluate system response from different torque and speed inputs. During the test, it is important that the oil within the gearbox system is maintained at a specific temperature regardless of the inputs. Therefore, an external oil temperature control system was established to control the oil temperature.

The current solution in Scania is to combine both the oil temperature control system and the customer's gearbox system into one model, which is known as the *gearbox oil conditioning system.* A manually-tuned PI controller is then implemented to control the oil temperature within the gearbox system. There are four main reasons for Scania to take this approach:

1. The numerical model of their customers' gearbox systems are not provided.
2. It is not possible to derive the gearbox system models due to the time limitation of each test.
3. The load cycles for the dynamometer are not communicated to the NLRI group before testing.
4. The derived gearbox system model lacks portability since each product is unique.

Although this solution provides acceptable results, there are two main problems with the current approach:

- Time inefficiency

  The test operator has to wait at least 40 minutes between each test run for tuning PI controller parameters since the system requires at least 20 minutes to heat up and then an additional 20 minutes to cool down the oil within the gearbox system. According to Scania, it takes an average of 80 hours to find acceptable parameters for the PI controller, and this is just for one gearbox setup.

- Control performance

  Due to the nature of iterative manual tuning, the performance of the controller (such as rise time, settling time and error tracking) are only acceptable and better performance is desired.

One way in which the time inefficiency and control performance could be improved upon is by deriving a numerical model of the physical system and build a controller based on the simulated system. Unfortunately many challenges exist in deriving a mathematical representation of the system plant, so a simulation is not currently viable. For one, the dynamics of the heat exchanger is inherently nonlinear and therefore a numerical model is not easily derived. The system also has many sources of disturbance and noise that are impossible to model without extensive testing and apriori knowledge on the required testing. These includes, but is not limited to, variables such as the input dynamometer torque/speed, heat loss to ambient environment, varying flow rates between different gearboxes, and delays in systems based on specific test setups. Another issue toward deriving a mathematical representation is the many unknown parameters/attributes of the entire system. Data sheets and attributes for many of the used components, such as flow rates, heat transfer coefficients, fluid properties, and more, are not readily known by the NLRI group and change depending on the particular test setup.

A common alternative approach for such a case, where physical properties are impossible to discern, is through system identification with data-driven methods. For instance, the researchers involved with paper [9] worked on a a soft robotics quadruped where they dealt with a nonlinear multiple-input multiple-output (MIMO) system that was un-unidentifiable. MATLAB's system identification toolbox was therefore used and due to the knowledge of their MIMO system, a state-space parametric modelling structure approach was used. Fit was found to be $\approx 83\%$ accurate using a 3rd order model of this type and an linear quadratic regulator (LQR) model-based controller was then successfully derived from this.

Another example is shown in paper [10] where 3D printing in conjunction with shape memory polymers is discussed. Polymer structures move based on temperature that is altered by an input voltage. This system is nonlinear and difficult to numerically model so data-driven modelling methods are again used to discern the discrete first-order transfer function between the normalized temperature and squared electric voltage inputs. A PI controller with anti-windup is then derived from this transfer function that ensures no overshoot and a quick rise-time.

Paper [11] discusses the possibility of obtaining the model for a nonlinear electro-hydraulic actuator servo system with observed data of input and output. The researchers used autoregressive with extra input model (ARX) and autoregressive moving average with extra input model (ARMAX) system structures for data-driven modelling that emulate the system without the need of prior knowledge of the physical system. With the appropriate sampling time and fine-tuning of the model parameters, the estimated models reached a best-fit percentage of over 90%.

In [12], a construction of a nonlinear wind signal forecasting system was studied. The researchers managed to construct a suitable model for wind signals forecasting in a wind electric farm using the autogregressive moving average model (ARMA) modelling approach. The results yielded an average relative error of 6.9%, and an improvement to wind signal predicting error from 25%-40% to 16.1%.

In [13], system identification was used to estimate a model consisting of a plate being heated by a halogen light bulb. ARX, ARMAX, and Box-Jenkins model (BJ) system modelling approaches were investigated to determine the best fit to actual output data. Ultimately it was found that a ARMAX time-series approach sufficiently modelled their system. This is somewhat similar to the presented gearbox scenario in regards to heat transfer being the main physical phenomena. However their scenario is a linear case involving radiative heat transfer, whereas the oil conditioning shell-and-tube heat exchanger is inherently nonlinear and the entire system is exposed to drastically larger amounts of noise and disturbances mentioned previously. Given these large differences, it brings to question whether a similar approach would be viable in the proposed gearbox oil-conditioning system's case.

Therefore, the first part of this master thesis aims to conduct a replicate study of [13], where various methods of system identification are conducted using MATLAB's system identification toolbox and then are analyzed for best-fitment. By doing so, it can validate/disprove whether the same approach holds true in a more complex system in terms of non-linearity and more prevalent system noises and disturbances. The proposed study would be tested and validated on one specific gearbox oil conditioning system.

The second part to this master thesis is to then design a PI controller by means of pole placement that can be base on the derived data-driven estimated model of research question one. Pole placement is a widely used controller design method both in academia and industry; for instance, with the design of the Takagi Sugeno Kang (TSK) fuzzy controller [14] or the balancing controller of a two wheels mobile robot [15]. This method is considered a model-based control method as it uses knowledge of the closed-loop poles to then design parameters which ensure stability while tuning system response, such as with faster/slower rise time, tracking error, and setting time. Manually tuned PI parameters cannot ensure the same and is a inefficient, iterative process in comparison.

4 Research Questions

- Can the approach to system identification used in paper [13] be upscaled into a more complex gearbox oil conditioning system with nonlinear dynamics and extensive system noise and disturbances?
- In terms of rise time, settling time, error tracking, how would the performance between a manually-tuned PI controller and a pole placement based PI controller compare?

5 Methodology

Research question 1 is a quantitative question in that it aims to establish a more accurate solution for the gearbox oil conditioning system's model. By using the MATLAB's system identification toolbox on test data, an approximated system model can be created using various data-driven modelling approaches as used in paper [13]. Similar to this paper, further analysis will be conducted on the resulting models to determine which approach provides the most accurate model estimation. Such performance criteria include: (1) smallest final prediction error (FPE), (2) largest normalized root mean square) (NRME) percentage, and (3) auto-correlation and cross-correlation analysis of residuals that are contained within confidence region.

A procedural outline for answering this first research question is then as follows:

1. Study the dynamics to estimate polynomial structure

2. Collect measured data from the gearbox test run, where disturbance is kept nominal and input is varied, and split into two sets (one set for model creation and the other for independent model validation)

   (a) Input (valve percentage), output (gearbox oil temperature; inlet or outlet), and time stamp

3. Perform model estimation and fine tune with ARX model approach for system identification

   (a) Fine tune with possible changes to polynomial order, noise, delays, etc.

4. Perform model validation and analysis with the above mentioned performance criteria

5. Repeat step 3 and 4 with ARMAX, BJ and additional parametric modelling approaches

6. The best estimated model is identified and the results are recorded for use in the controller design of research question 2

Research question 2 is also a quantitative question, which aims to compare the performance between a manually-tuned and a pole placement based controller for the gearbox oil conditioning system. This comparison of the performance includes the rise time, settling time, and error tracking of the system. The control method with the lowest rise time, settling time, and error is deemed to have better performance.

The steps involved in answering research question 2 are as follows:

1. Design the controller using pole placement method to ensure stability and performance

2. Implement the controller in TwinCAT 3

3. Measure the performance of the controller (rise time, settling time, error tracking)

4. Refining the placement of poles and zeros of the pole placement based controller

5. Provide evidence to prove that the pole placement based controller can indeed provide better performance to the gearbox oil conditioning system (quantifying the performance metrics)

Bibliography

[1] *Om Scania Södertälje*. Scania Södertälje. URL: https://www.scania.com/scaniasodertalje/sv/home/om-scania-sodertalje.html (visited on 12/26/2021).

[2] J B. Winther. *Dynamometer Handbook of Basic Theory Applications*. Cleveland, Ohio: Eaton Corp, 1975.

[3] Frank P. Incropera and P. DeWitt David. *Fundamentals of Heat Transfer*. 5th ed. Hoboken, NJ: John Wiley & Sons, 2007. ISBN: 9780471457275.

[4] *What is LabVIEW?* URL: https://www.ni.com/sv-se/shop/labview.html (visited on 12/26/2021).

[5] Aghareed Tayeb et al. "A new dynamic model for a shell-and-tube heat exchanger". In: *Energy Conversion and Management* 32 (Dec. 31, 1991), pp. 439–446. DOI: 10.1016/0196-8904(91)90005-4.

[6] Stephen J. Dodds. "Plant Modelling". In: *Feedback Control: Linear, Nonlinear and Robust Techniques and Design with Industrial Applications*. Ed. by Stephen J. Dodds. Advanced Textbooks in Control and Signal Processing. London: Springer, 2015, pp. 73–167. ISBN: 9781447166757. DOI: 10.1007/978-1-4471-6675-7_2. URL: https://doi.org/10.1007/978-1-4471-6675-7_2 (visited on 12/27/2021).

[7] Torsten Söderström and Petre Stoica. *System Identification*. University Press, Cambridge (UK): Prentice Hall International, 2001. ISBN: 0138812365.

[8] Beckhoff Automation GmbH Co KG. *TwinCAT — Automation software*. URL: https://www.beckhoff.com/en-en/products/automation/twincat/ (visited on 12/27/2021).

[9] Seshagopalan Thorapalli Muralidharan and Zhu Ruihao. "Continuum Actuator Based Soft Quadruped Robot". In: *2021 IEEE 17th International Conference on Automation Science and Engineering (CASE)* (2021).

[10] Ji Qinglei, Chen Mo, and Zhao Chun. "Feedback Control for the Precise Shape Morphing of 4D-Printed Shape Memory Polymer". In: *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 68, NO. 12, DECEMBER 2021* (2021).

[11] T. G. Ling et al. "System Identification of Electro-Hydraulic Actuator". In: *2011 4th International Conference on Mechatronics (ICOM)* (2011).

[12] Shiqiong Zhou et al. “Wind Signal Forecasting Based on System Identification Toolbox of MATLAB”. In: *2013 Third International Conference on Intelligent System Design and Engineering Applications* (2013).

[13] Muhammad Junaid Rabbani et al. “Model Identification and Validation for a Heating System using MATLAB System Identification Toolbox”. In: *IOP Conference Series: Materials Science and Engineering* (2013).

[14] G.B.Kang, W.Lee, and M.Sugeno. “Design of TSK fuzzy controller based on TSK fuzzy model using pole placement”. In: *1998 IEEE International Conference on Fuzzy Systems Proceedings. IEEE World Congress on Computational Intelligence (Cat. No.98CH36228)* (1998).

[15] N.M.Abdul Ghani et al. “Two wheels mobile robot using optimal regulator control”. In: *2010 10th International Conference on Intelligent Systems Design and Applications* (2010).