# Investigation of Performance Differences and Control Synthesis for Servo-Controlled and Vacuum-Actuated Wastegates

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## 1. Abstract

Turbocharging plays an important role in the downsizing of engines. Model-based approaches for boost control are going to increasing the necessity for controlling the wastegate flow more accurately. In today's cars, the wastegate is usually only controlled with a duty cycle and without position feedback. Due to nonlinearities and varying disturbances a duty cycle does not correspond to a certain position. Currently the most frequently used feedback controller strategy is to use the boost pressure as the controller reference. This means that there is a large time constant from actuation command to effect in boost pressure, which can impair dynamic performance. In this paper, the performance of an electrically controlled vacuum-actuated waste-gate, subsequently referred to as vacuum wastegate, is compared to an electrical servo-controlled wastegate, also referred to as electric wastegate. Their performance is investigated with the two actuators installed on a turbocharged inline four gasoline engine in an engine test bench. Furthermore, different control synthesis designs for these different actuators are investigated. A state-feedback controller with standard models for the electric wastegate is described and implemented, which gives a position-controlled wastegate. One main difference between vacuum and electric wastegate is that the latter has a position sensor. To make an extended comparison between the solutions, the vacuum wastegate is also equipped with a position sensor and controller using standard controller design methods. The controllers are implemented and compared both in a simulation environment and evaluated in an engine test bench. In addition, for the electric wastegate, both soft-landing and tightening features are also implemented and investigated. Their aim is to improve the lifetime and behavior at or near the closed position.

## 2. Introduction

Turbocharging is an important part of downsizing engines to deliver the amount of air needed for stoichiometric combustion. Control of the turbocharger is performed with the use of a wastegate valve. This wastegate valve is often controlled by a pneumatic actuator that moves a rod back and forth by changing the pressure, and thereby changes the position of the wastegate valve. In Mehmood's doctoral thesis [1], physical modeling and simulation of the Electro-pneumatic Pressure Converter (EPC) and the pneumatic wastegate actuator are performed for a Variable Geometry Turbocharger. It shows that extensive modeling is needed to model the nonlinearities in the actuator.

[2] proposes a controller design that is based on Internal Model Control (IMC). This results in a PID-controller that acts on feedback from the boost pressure. Variants of this method also exist, but the common factor is that it usually is single-input single-output (SISO) controllers that are used to control the boost pressure, with the wastegate control signal as input and the boost pressure as output. The development of the air charge system is becoming more complex, and looking at diesel engines, their also are multiple stage turbochargers and different exhaust gas recirculation (EGR) solutions that all affect the boost pressure. Development of gasoline engines is also believed to also incorporate these types of solutions in the future. This is going to transform boost pressure control into a control system with multiple inputs and usually a reduced sensor setup. Therefore models play an important role by giving information about different required states. This is one of the reasons for carrying out the investigation done in this paper: it is believed that knowing and controlling the state of wastegate position will aid the development of more accurate models for the air charge system.

In this paper, an investigation of electric wastegate and vacuum waste is performed, and controllers for the position of the actuators are developed and compared. The controllers are developed using the same level of complexity of system model and control methods, respectively. It will be shown that the electric wastegate is easier to control than the vacuum wastegate. More advanced control methods are needed to accurately control the wastegate position with the vacuum wastegate.

This paper is organized as follows: Section 3, presents a description of the hardware used for this paper. After that, modeling of the two actuators is described in Section 4. Control synthesis for both actuators and the complementary features for the electric wastegate are presented in Section 5. Results from simulations and engine measurements are shown in Section 6, followed by a discussion of results in Section 7. Lastly, the conclusions drawn in this paper are presented in Section 8.

## 3. Experimental Setup

The engine used for the measurements in this paper is an inline four 2 liter gasoline engine with a single turbocharger mounted in an engine test bench. Two different wastegate actuators have been used. One named *electric wastegate*, consisting of an electric motor driven with a Pulse-Width Modulation (PWM) signal and a position sensor. The other actuator is the electrically controlled vacuum-actuated wastegate that does not have a position sensor but for this study is equipped with one. The vacuum wastegate used is of the type described in [3] and [1], where a pressure difference compresses a spring that opens the wastegate valve, with ambient pressure as maximum. A vacuum in a vacuum tank is generated with a vacuum pump driven by the camshaft. No difference in vacuum has been seen for different engine speeds. Whereas transients in wastegate duty cycles have a small effect on the vacuum. When the pressure difference is zero the spring force closes the wastegate valve.

## 4. Modeling of Actuators

This section describes the modeling of the different actuators. When the wastegate position is presented as percentage, 100 % represents fully closed and 0 % is fully open.

### *Electric Servo Modeling*

In [4], an electric motor that drives the actuator is described by the transfer function

$$G_{motor}(s) = \frac{K_{motor}}{(sT_{motor}+1)\,s} e^{-sL_{motor}} \tag{1}$$

where $K_{motor}$ is the static gain, $T_{motor}$ the time constant and $L_{motor}$ the time delay. The transfer function describes how the end position of the actuator is produced by the input PWM signal. Linear dynamics for the actuator motor are assumed and the backlash effect in the built-in gearbox is considered small and negligible. In (1) the factor $\frac{K_{motor}}{sT_{motor}+1}$ can be seen as the transfer function from a PWM signal to the speed of the actuator, the factor $\frac{1}{s}$ is the integrator for the speed and therefore gives the position of the actuator. In other words, the PWM signal generates torque that drives the motor shaft, making the positions to accumulate. When the input signal stops, the actuator will be slowed down by friction and eventually come to a stop. As the transfer function in (1) has a pole in $s = 0$, it is unstable for a constant input signal. Therefore a step response in input signal is not a good choice for system identification. For system identification, the system is instead fed with square pulses as input signal to capture the dynamics during acceleration and deceleration. With measurements of the position during these pulses, one can calculate the speed of the actuator and identify $K_{motor}$ and $T_{motor}$ in (1). A validation of the model can be seen in Figure 1, where the estimated fitness of the model is calculated as the normalized root-mean-square deviation defined as

$$\text{fit} = 100\left(1 - \frac{\|y-\hat{y}\|}{\|y-\bar{y}\|}\right) \tag{2}$$

where $\hat{y}$ is the model output and $\bar{y}$ is the mean of $y$.

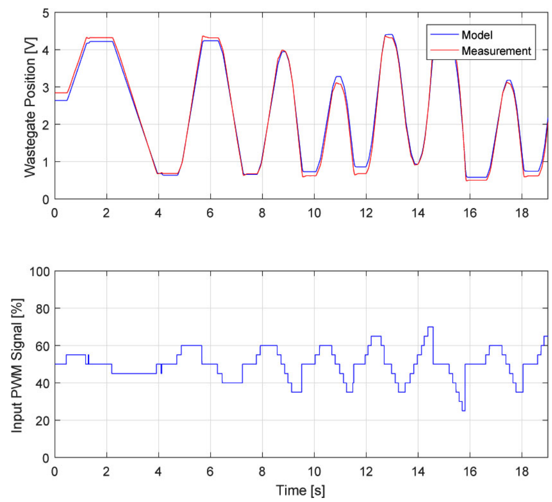


Figure 1. Validation of the estimated model using data that has not been used for identification. The input PWM signal consists of different steps and the model fit calculated with (2) is 89.88 %. As seen in the figure the model captures the dynamics well and only deviates a little in static levels. When the PWM signal is 50 % no torque is applied. A larger PWM turns it towards opening and a lower PWM towards closing.

The time delay of the system was measured to approximately 19 ms which is the same as 19 samples. Ignoring the time delay gives the following state space representation of the model

$$\begin{aligned}
\dot{x} &= Ax + Bu \\
y &= Cx \\
x &= \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \qquad A = \begin{bmatrix} -\frac{1}{T_{motor}} & 0 \\ 0 & 1 \end{bmatrix} \\
B &= \begin{bmatrix} \frac{K_{motor}}{T_{motor}} \\ 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 1 \end{bmatrix}
\end{aligned} \tag{3}$$

where $x_1$ denotes the state for speed and $x_2$ denotes the state for position. For simplicity, the time delay was ignored in the control system. For use in a control system, a discrete state space model is also needed in the form

$$x[k+1] = Fx[k] + Gu[k]$$
$$y[k] = Hx[k]$$
$$x[k] = \begin{bmatrix} x_1[k] \\ x_2[k] \end{bmatrix} \qquad H = \begin{bmatrix} 0 & 1 \end{bmatrix} \tag{4}$$

where $F$ and $G$ are the discrete state space matrices. Because the control system is a zero-order hold system, [5] shows that the discrete state space matrices can be calculated as

$$\text{EXPM}\left(\begin{bmatrix} AT_s & BT_s \\ 0 & 0 \end{bmatrix}\right) = \begin{bmatrix} F & G \\ 0 & I \end{bmatrix} \tag{5}$$

where EXPM stands for matrix exponential. Matrices $A$ and $B$ are given in (3), and $T_s$ is the sample time.

## *Vacuum-Actuator Modeling*

The pneumatic actuator consists of two systems that can be seen as separate from each other. The first system is the EPC; it converts a PWM signal to a pressure. The second system is the pneumatic actuator controlling the wastegate where the pressure from the EPC is the input. A simple overview of the system is shown in Figure 2.

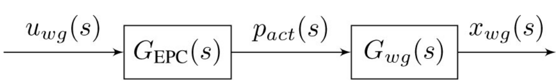


Figure 2. Overview of the vacuum actuator systems. $G_{\text{EPC}}(s)$ is the EPC system that receives a duty cycle, $u_{wg}(s)$, as input and gives an actuator pressure, $p_{act}(s)$, as output. The wastegate actuator is described by $G_{wg}(s)$ which takes $p_{act}(s)$ as input and wastegate position, $x_{wg}(s)$, as output.

For the vacuum wastegate, it is shown in [6] that there is nonlinear hysteresis between actuator pressure and position of the actuator, mainly because of friction. This is also confirmed in [3] which also shows that the hysteresis can vary much between different actuators. The hysteresis is therefore needs to be investigated for the modeling of the actuator. In Figure 3 hysteresis is observed between duty cycle to the EPC and the actuator pressure, however no clear hysteresis can be seen between the actuator pressure and its position in Figure 4. Investigating duty cycle to EPC and actuator position a combination of these two are expected and can be seen in Figure 5. Because of the small hysteresis for the actuator a linear approximation from duty cycle to position can be defined as

$$f_{wg}(u_{wg}) = \begin{cases} 0, & u_{wg} < c_{wg,min} \\ c_1 u_{wg} + c_2, & c_{wg,min} \leq u_{wg} \leq c_{wg,max} \\ 100, & u_{wg} > c_{wg,max} \end{cases} \tag{6}$$

where $f_{wg}(u_{wg})$ is the static compensator for the actuator position between 0 % and 100 %, $c_{wg,min}$ and $c_{wg,max}$ are estimated constants defining lower and upper limits respectively for where the position is considered either opened or closed. Slope of the line is given by $c_1$ and the interception of the y-axis is $c_2$.

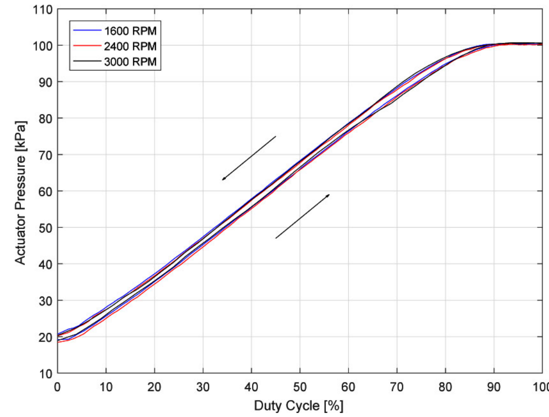


Figure 3. Ramp in Duty Cycle from 0 % to 100 % and 100 % to 0 %, done for three different operating conditions of the engine. Ramping of the signal was done slowly to ensure that no system dynamics are seen. Hysteresis can be seen in the pressure that is controlling the wastegate actuator.

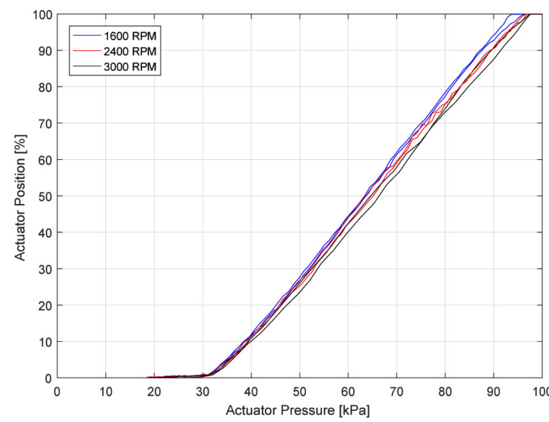


Figure 4. Same experiment as in Figure 5 showing how the pressure controlling the wastegate actuator affects its position. No clear hysteresis can be seen and it looks like there is a linear relationship between actuator pressure and its position.

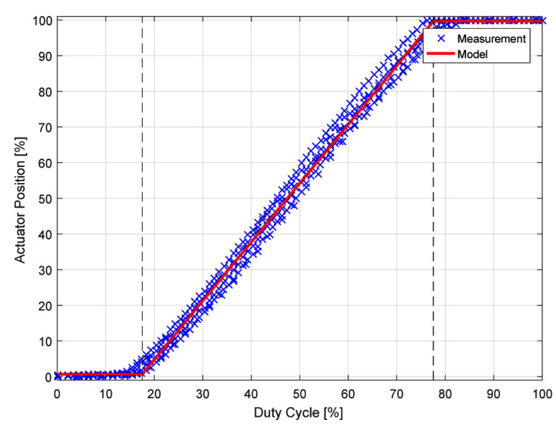


Figure 5. Actuator position with a ramp in duty cycle as input. It is seen that it is a combination of duty cycle to actuator pressure, and actuator pressure to actuator position. A linear model is approximated as the red line in (6) and the blue crosses are the combined measurements from three different operating conditions of the engine.

For identification of the dynamics of the system, steps in duty cycle can be performed while measuring actuator pressure and position. A sequence from the identification data is seen in Figure 6 where it is seen that the dynamics differ much between opening and closing of the wastegate. When closing the wastegate and the duty cycle is not 100 %. The wastegate position makes an initial jump and then a slow movement to the final position. On the other hand, when sending 100 % duty cycle, the wastegate closes much faster and shows the same sort of dynamics as for the opening of the wastegate. This seems to be because of an internal behavior in the EPC that is not seen in the static measurements, but that becomes apparent when studying the dynamics. It is possible to see this difference in the dynamics in Figure 6 if the actuator pressure is observed at around 30 s where a step to 100 % duty cycle is happening. The pressure dynamics for the actuator pressure are much faster in that step than the one that occurs at around 18 s. In this paper, the focus lies on the comparison between vacuum and electric wastegate. Therefore extensive modeling of the vacuum wastegate is not performed and a first order system is approximated for the vacuum wastegate as

$$G_{vac,act}(s) = \frac{f_{wg}(u_{wg})}{sT_{wg}+1} \tag{7}$$

where $f_{wg}(u_{wg})$ is the nonlinear compensator described by (6) and $T_{wg}$ is the time constant. Validation of the estimated model is seen in Figure 7 where the errors in the nonlinear compensator are seen as static errors. Model fit using normalized root-mean-square deviation as defined in (2) is 83.71 %. Due to the nonlinearities in the system a low model fit is to be expected. Therefore the model will only be used for controller design and not for simulation of the system. For use in simulation the nonlinearities need to be captured and implemented to get an accurate representation (for the interested reader this is done in [1]).

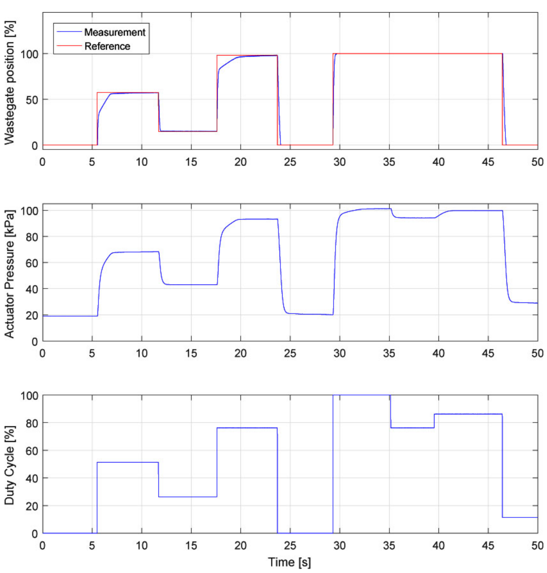


Figure 6. Showing identification data for the vacuum model. Steps in duty cycle were performed and both actuator pressure and wastegate position were measured. The reference in the top plot is only showing the step in duty cycle scaled to fit wastegate position to have as a reference. It is seen that the wastegate position dynamics are not the same for closing and opening.

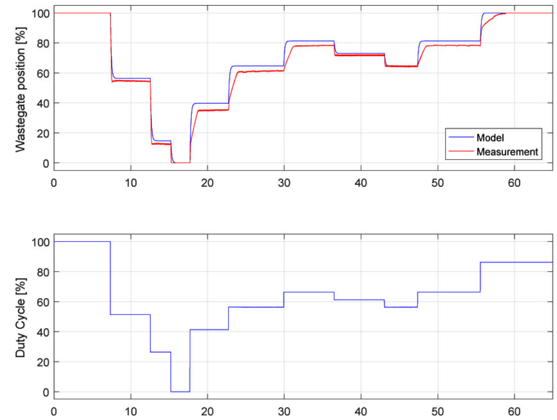


Figure 7. Validation of the estimated model using data that has not been used for identification. The nonlinear compensator is used with duty cycle as input to generate the input to the model. Different steps are performed in the duty cycle and the position is measured. Model fit calculated with (2) is 83.71 %. As seen in the figure the model captures the opening dynamics well. Errors in the nonlinear compensator are also seen in the static errors.

## 5. Controller Design

In this section, the design of the position controllers for the actuators are presented.

### *Electric Wastegate Controller*

The choice of controller for the electric servo is a state-feedback controller. A functioning state-feedback controller requires all states of the system to be known, in this case speed and position. The only measurable state is the position, which implies that an observer is needed to estimate the state of speed in order to fully take advantage of state-feedback control. Discrete Kalman filter based observer is used for the estimation. State representation used in the Kalman filter is the one described in (4). Covariance matrices for the process noise and the measurement noise are tuned manually. Implementation details about discrete Kalman filter are thoroughly described in [7]. The control signal for state-feedback controller is explained in [4] as

$$u = -Lx + l_0 r \qquad\qquad L = \begin{bmatrix} l_1 & l_2 \end{bmatrix} \tag{8}$$

where $r$ is the control set-point, $L$ is the state-gain, and $l_0$ is a correction term that ensures that the static gain of the closed system remains 1. In [4] the optimal choice of L can be formulated as a linear quadratic optimization criteria

$$J = \int_0^\infty \left(x^T(t)Qx(t) + u^2(t)\right) \mathrm{d}t$$
$$Q = \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix}, \qquad\qquad x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{9}$$

where $J$ is the cost function that will be minimized. The diagonal penalty matrix $Q$ decides how big impact each state has on the cost function. As for the actuator that reaches and holds a position, a penalty of the state of position is desired. $x_1$ and $x_2$ are states for speed and position respectively, which means that $q_2$ shall have greater weight than $q_1$. The solution $u$ that meets the optimization of the cost function is

$$u = -Lx = -B^T P x \Rightarrow L = B^T P \tag{10}$$

in which $P$ solves the algebraic Riccati equation

$$Q + A^T P + PA - PBB^T P = 0 \tag{11}$$

with $A$,$B$, and $Q$ defined in (3) and (9). To ensure the static gain of the closed system to be 1, $l_0$ is chosen as equal to $l_2$, thus

$$u = l_2 r - l_2 \hat{x}_2 - l_1 \hat{x}_1 = l_2(r - \hat{x}_2) - l_1 \hat{x}_1 \tag{12}$$

where $\hat{x}_1$ is the actuator speed and $\hat{x}_2$ is the actuator position, which of both are estimated by the observer. When the controller is applied on the physical actuator, it may be needed to introduce an integration part to eliminate static errors. Although the actuator motor itself contains a natural integrator, factors as friction and limited control signal resolution may still cause static errors if only the state-feedback controller is used. In Figure 8 an overview of the state-feedback controller is shown without extra integration part.

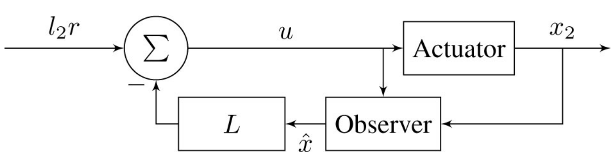


Figure 8. Overview of the system with both observer and state-feedback implemented with control signal $u$ defined as in (12). If needed, the correction term from integration of the error can be added to the sum.

### Complementary Electric Wastegate Features

To improve the lifetime of the electric motor, complementary features are implemented: soft-landing, tightening, auto-find of end positions, and to not control against exhaust pulsations. Soft-landing, tightening, and auto-find of end positions are features proposed in [8].

### Soft-Landing and Tightening

Soft-landing is to protect the actuator from crashing into the hard stops by reducing the control signal near the end positions, and the tightening is to apply more power when closed wastegate is demanded.

### Avoid Control Against Pulsations

To avoid having the controller action excited by pulsations in the exhaust system, the measurement of the position is low-pass filtered with a cut-off frequency below the frequency of the opening of exhaust valves. Cut-off frequency for the low-pass filter could therefore be chosen as

$$f_{cutoff} = n_v \frac{N_e - \Delta N_{margin}}{60} \text{ [Hz]} \tag{13}$$

where $n_v$ is the number of exhaust valve openings per engine revolution, and $\Delta N_{margin}$ is a design margin in Revolutions Per Minute (RPM) that offsets the engine speed, $N_e$ RPM, to damp the pulsation frequency.

### Auto-Find End Positions of Wastegate

Auto-find function of end positions is a calibration that automatically detect and store end positions of the wastegate. During the calibration the position controller is deactivated and the actuator performs an up-sweep and down-sweep in low speed to find the upper bound and lower bound respectively. Identification of the end positions can be done by supervising the position derivative, in other words the change rate of position. When the actuator is in motion, the derivative is non-zero. When the actuator is stuck in an end position the derivative ought to be zero, however due to the presence of measurement noise it is difficult to have a pure series of consecutive zeros to establish a confirmation. The identification is made robust by using Cumulative SUM (CUSUM) algorithm mentioned in [9]. CUSUM algorithm is based on the following recursive function

$$T[k] = \max(0, T[k-1] + r[k-1]), \quad T[0] = 0 \tag{14}$$

In this application: $r = -1$: position derivative greater than derivative threshold. $r = 1$: position derivative smaller than derivative threshold. The introduction of derivative threshold aims to provide flexibility in the detection. When an end position is reached, the position derivatives will more likely to be considerably smaller than that during motion, leading to increasing $T[k]$. $T[k]$ will then be constantly compared to a threshold value for CUSUM. A confirmation is generated as $T[k]$ exceeds the CUSUM-threshold and the current position is remembered as an end position. As soon as the confirmation for the upper end position is dispatched, the actuator reverts direction and the same method is applied to find the lower end position. When both positions are identified and stored, the controller proceeds to function normally.

### Vacuum Wastegate Controller

For the vacuum wastegate controller, the design method evaluated is lambda tuning. Lambda tuning is a well known design method and it is described in many literatures, for example in [10]. The concept for the lambda tuning is to specify the time constant for the open system and the desired time constant for the closed system with the parameter $\lambda$ defined as

$$\lambda = \frac{T_{closed}}{T_{open}} \tag{15}$$

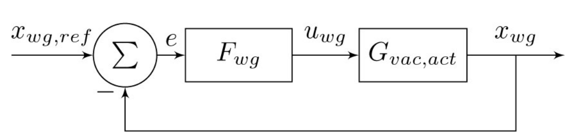


Figure 9. Overview of the closed system. The controller is defined as $F_{wg}$ and the system is represented by $G_{vac,act}$. Position reference is $x_{wg,ref}$

where $\lambda < 1$ gives a faster closed loop system and $\lambda > 1$ a slower closed loop system. With the structure of the controller described as in Figure 9 the closed system is described as

$$G_c = \frac{F_{wg} G_{act,vac}}{1 + F_{wg} G_{act,vac}} \tag{16}$$

and the desired closed system is

$$G_{c,desired}(s) = \frac{K}{sT_{closed} + 1} = \frac{K}{s\lambda T_{open} + 1} \tag{17}$$

Now if setting (16) = (17) and solving for $F_{wg}$ one gets

$$F_{wg}(s) = \frac{1}{K\lambda}\left(1 + \frac{1}{T_{open}s}\right) \tag{18}$$

which is a PI-controller. Using the model for the vacuum wastegate that was parameterized in previous section and described by (7) the controller is described by

$$F_{wg}(s) = \frac{1}{g(f_{wg}(u_{wg}))\lambda}\left(1 + \frac{1}{T_{wg}s}\right) \tag{19}$$

where $g(\cdot)$ is a function that gives the voltage from the position sensor of the wastegate actuator with actuator position in percentage as input. In (19) it is seen that $g(\cdot)$ is in the denominator and therefore must never output value 0. As seen in Figure 10, $g(\cdot)$ is strictly positive because the actuator position can never be bigger than 100 % and the function is also monotonically decreasing. For implementation in a control system the controller needs to be converted into a discrete representation. As described in [10] with the use of backward Euler method the difference form of the PI-controller in (19) becomes

$$\begin{aligned} v[k] &= u[k-1] + \frac{1}{g(f_{wg}(u_{wg}))\lambda}\left(1 + \frac{T_s}{T_{wg}}\right)e[k] \\ &\quad - \frac{1}{g(f_{wg}(u_{wg}))\lambda}e[k-1] \\ u[k] &= \begin{cases} u_{max}, & \text{if } v[k] > u_{max} \\ v[k], & \text{if } u_{min} \le v[k] \le u_{max} \\ u_{min}, & \text{if } v[k] < u_{min} \end{cases} \end{aligned} \tag{20}$$

where $u$ is the control signal. Noticeable is that a controller on this form is already protected against integrator windup because no state in the controller is accumulating if the control signal saturates.

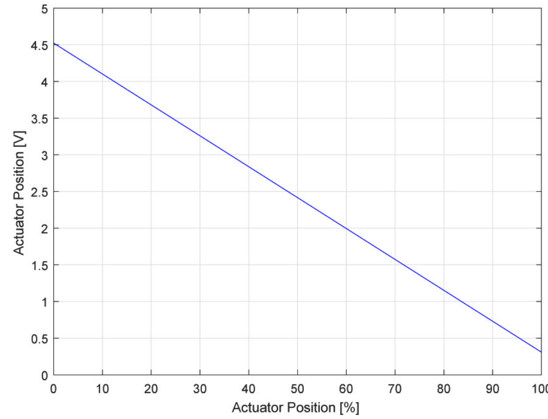


Figure 10. Function $g(\cdot)$ that converts an actuator position given in percentage to a position in voltage corresponding to the position sensor. It is seen that $g(\cdot)$ is strictly positive and monotonically decreasing. Actuator position can never be bigger than 100 %.

## 6. Results

In this section the wastegate controllers are evaluated on an engine in an engine test stand. This means that there are disturbances influencing the controllers.

### *Electric Wastegate*

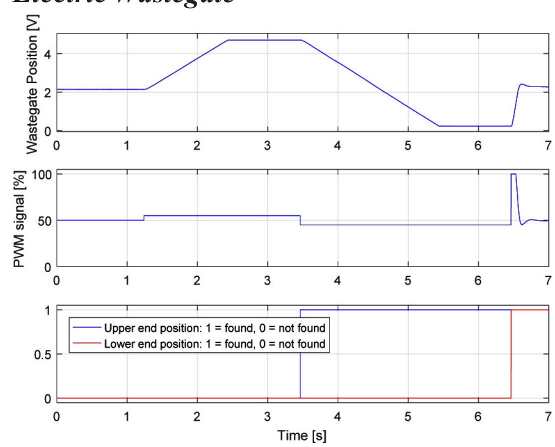


Figure 11. The auto-find function is executed to set upper and lower limits for the electric wastegate. As seen in the figure the upper end position is found after approximately 3.5 s and the lower position is found after approximately 6.5 s. Afterwards the controller began to maintain the demanded position set point.

Validation of the soft-landing, tightening, auto-find, and simulation environment are presented in earlier work done in [11] but the results are extracted to this paper to show a complete implementation on a real engine. Figure 11 shows how the auto-find function is initiated to find the upper and lower bound for the wastegate positions. Validation of the simulation environment built with the model described by (1) is shown in Figure 12 where it is compared with actuator measurements. Demonstration of how the tightening and soft-landing works is shown in Figure 13 where the soft-landing when activated allows only a PWM signal in the range of 40 % to 60 %, and the tightening function applies an extra PWM signal of 5 %. Steps in position reference performed while engine running at 2400 RPM with a fixed throttle position of 25 % open are shown in Figure 14 and Figure 15. The electric wastegate makes a small overshoot both when closing and opening. Comparing opening and closing, the electric wastegate is behaving in the same way with only a slight difference in control signal. In Figure 16 the operating conditions of the engine are changed to 3000 RPM and the throttle is still fixed at 25 % open. A sequence of steps in position reference are performed and the electric wastegate follows the reference well both when closing and opening.

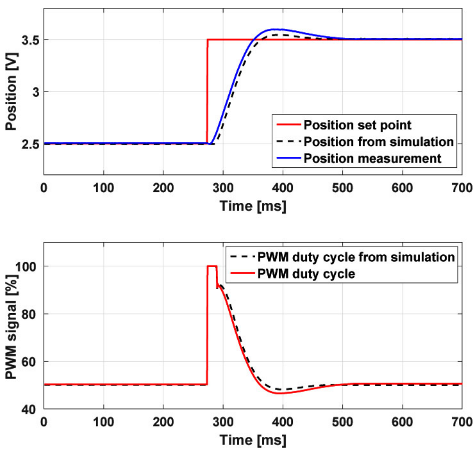


Figure 12. Validation of simulation environment for the electric wastegate, the figure is extracted from the results in [11]. The only manipulation is the y-axis for the PWM signal that now is in percentage. It is seen that the simulation environment is in good agreement with measurements performed with the actuator unit.

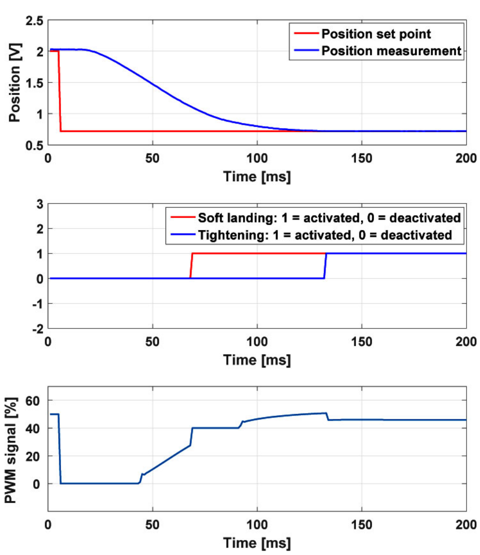


Figure 13. Demonstration of how the tightening function and also the soft-landing function manipulate the PWM signal. 50 % PWM signal corresponds to idle. It is seen that when the soft-landing is activated at 68 ms the PWM signal is directly saturated to 40 % which is 10 % from idle. Because a closed wastegate is demanded, at around 135 ms when the tightening is activated it is seen that the PWM signal jumps 5 % further away from idle which is the chosen reinforcement in PWM signal for tightening. The figure is extracted from the results in [11].

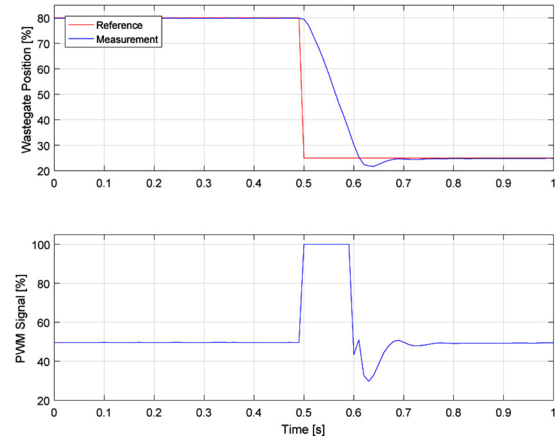


Figure 14. Engine is running at constant speed, 2400 RPM and the throttle is fixed at 25 % open. A step in position reference from 80 % to 25 % for the electric wastegate is performed at around 0.5 s. The controller is running at 1000 Hz both sampling and control signal but the measurements are only sampled at 100 Hz. This is the reason for the slope that is seen in the reference step and control signal at 0.5 s.

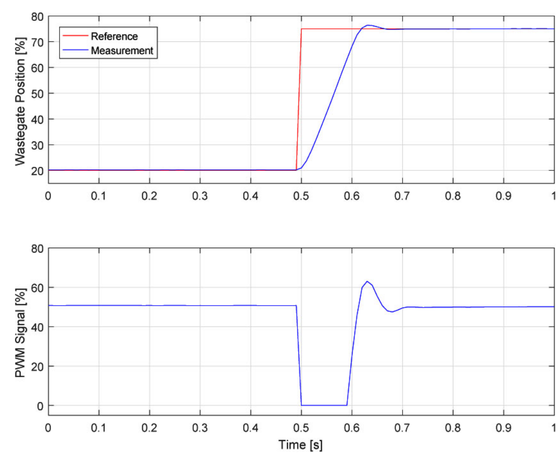


Figure 15. Engine is running at constant speed, 2400 RPM and the throttle is fixed at 25 % open. A step in position reference from 20 % to 75 % for the electric wastegate is performed at around 0.5 s. The controller is running at 1000 Hz both sampling and control signal but the measurements are only sampled at 100 Hz. This is the reason for the slope that is seen in the reference step and control signal at 0.5 s.

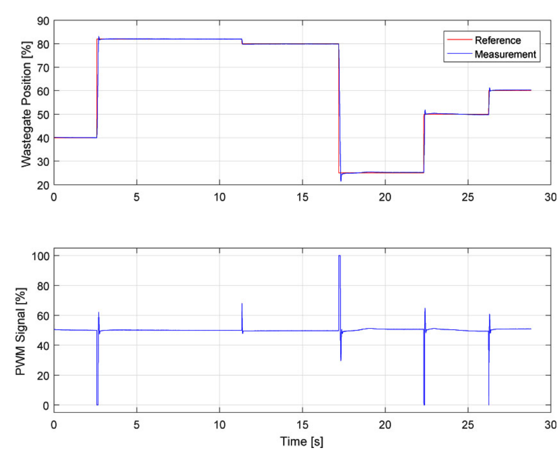


Figure 16. Engine is running at constant speed, 3000 RPM and the throttle is fixed at 25 % open. A sequence of steps are performed in position reference and it is seen that the electric wastegate controller is fast and accurate with small overshoots.

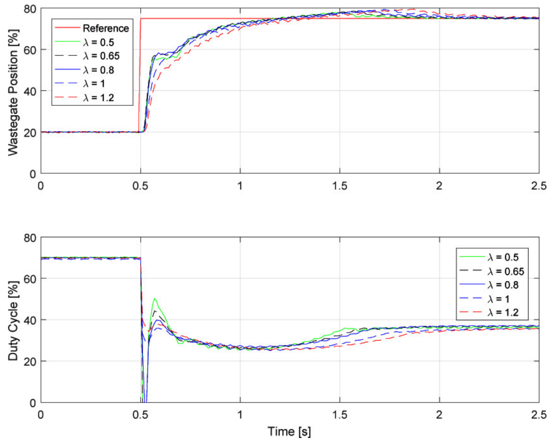


Figure 17. Engine is running at constant speed, 2400 RPM and the throttle is fixed at 30 % open. A step in position reference from 20 % to 75 % for the vacuum wastegate is performed at 0.5 s with different values of $\lambda$ described in (15). It is seen that when $\lambda \geq 1$ the control signal does not saturate. All settings reaches the set reference the first time after approximately 0.75 s.

### *Vacuum Wastegate*

It was shown that the vacuum wastegate has hysteresis. In Figure 6 it is shown that the dynamics between opening and closing of the wastegate differs. The controller described by (19) was implemented and position reference steps for closing and opening of the wastegate are shown in Figure 17 and Figure 18 respectively with different values of $\lambda$. During these tests the engine speed was 2400 RPM and the throttle was fixed at 30 %. For $\lambda \geq 1$ the control signal never saturates during the steps, the difference between the other $\lambda$ values are marginal. Closing and opening of the vacuum wastegate are very different, both in traveling and time to reach its new position reference after the step at 0.5 s. Operating conditions of the engine are changed to 3000 RPM and throttle position is fixed at 25 % in Figure 19, and different steps in position reference are performed. It is seen that the behavior between opening and closing are different and for some steps the overshoot is larger. Drops in control signal to 0 is because of the dead-zones in wastegate position shown in Figure 5.

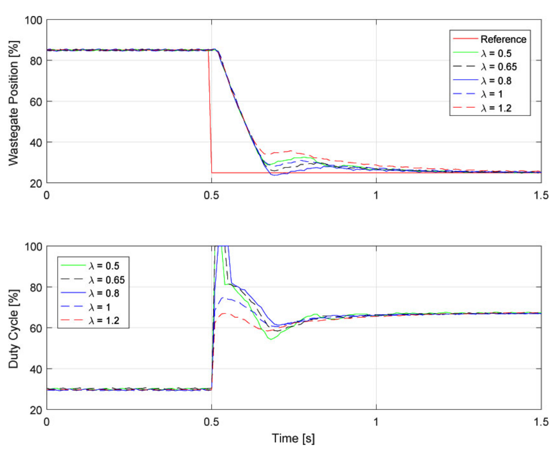


Figure 18. Engine is running at constant speed, 2400 RPM and the throttle is fixed at 30 % open. A step in position reference from 85 % to 25 % for the vacuum wastegate is performed at 0.5 s with different values of $\lambda$ described in (15). It is seen that when $\lambda \geq 1$ the control signal does not saturate. $\lambda = 0.8$ reaches the set point first.

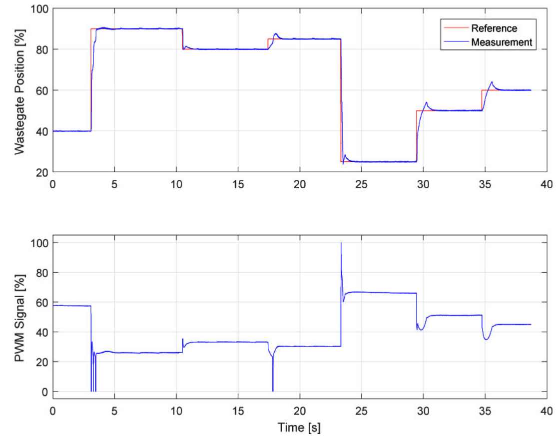


Figure 19. Engine is running at constant speed, 3000 RPM and the throttle is fixed at 25 % open. A sequence of steps are performed in position reference for the vacuum wastegate with $\lambda = 0.8$ in (15). Overshoots can be seen for most of the steps. The drops in control signal to 0 are because of the dead-zones in wastegate position that is seen in Figure 5.

## 7. Discussion

With the increasing demand of model-based designs for the air charge system, the wastegate actuator was investigated in this paper. Boost pressure is usually the feedback to the wastegate actuator, which means that there is a large time constant from the actuation command to the effect in boost pressure. It is believed by the authors that having an accurate insight and control of the wastegate helps the model-based approaches for boost pressure and torque control.

When comparing the actuators with the results in this paper, one could argue that a better and more complex model could be chosen for the vacuum wastegate and yield a better result. This may require other sensors than merely a position sensor, which would require more development and also result in higher production costs. Therefore it was chosen to apply the same model methodology for both actuators and investigate what could be achieved. The controller designs are different for both actuators where a state-feedback controller was considered more appropriate for the electric wastegate as its integrator was making the system unstable. The vacuum wastegate is a stable system, but the model was not good enough to capture the system dynamics well enough. Therefore a lambda-tuned PID controller was chosen. The performance results for the actuators are not supposed to be compared directly with each other. They are supposed to be used for identifying strengths and weaknesses in the different actuators.

### *Model Agreement and Design Choices*

As seen in the results, the vacuum wastegate is nonlinear from duty cycle to position and it also has different dynamics depending on whether the wastegate is opening or closing. The vacuum wastegate used in this paper is built so that the vacuum compresses the spring and therefore opens the wastegate, meaning that it is the spring force that closes the wastegate. As seen in Figure 17, when closing the actuator, it makes an initial jump in position and after that slowly approaches the position reference. This is in agreement with the behavior shown in duty cycle steps only in Figure 6 and the chosen controller in this paper does not take this behavior into account. For the opening of the vacuum wastegate shown in Figure 18, the behavior is more consistent and the model chosen for the controller seems to take the dominant dynamics into account. The difference in rise time between opening and closing of the vacuum wastegate is large, where closing takes the longest time. When closing, the wastegate needs to work against the exhaust mass flow and when opening it is the opposite, with the mass flow assisting the opening.

Looking at the electric wastegate, it is seen in the results that it follows the position reference accurately and fast, and it is hard to see any difference between opening and closing of the wastegate. The model chosen for the electric wastegate is in good agreement with the measurements seen in Figure 1. Features as tightening and soft-landing are also demonstrated with the latter not being a performance feature but rather increasing the actuator's lifetime.

### *Improvements of the Actuators*

A change of the spring in the vacuum wastegate would result in a different behavior for the actuator, where a stiffer spring would increase the tightening when closing the wastegate and also lower the time constant. It would on the other hand increase the time constant for the opening of the wastegate. It is therefore a trade-off in design between opening and closing. Another way to increase the applied force when closing and therefore lowering the time constant could be to actuate with a higher pressure than ambient pressure as maximum.

As for the electric wastegate, if the motor is changed it will affect the opening and closing of the wastegate in the same way. Therefore these types of performance design trade-offs do not exist.

## 8. Conclusions

In this work, a position controller for an electric wastegate is developed with the use of state-feedback control. As a comparison, a vacuum wastegate equipped with a position sensor is used and controlled by a PI-controller with parameters chosen with lambda tuning. The results are summarized as follows:

1. The electric servo for controlling the wastegate is easy to model and a state-feedback controller works well for controlling the wastegate position fast and accurately. The electric motor is also a linear system that behaves in the same way regardless if the wastegate is closing or opening.
2. Features like soft-landing, tightening and auto-find limits are demonstrated for the electric wastegate, where soft-landing is a feature that limits the control signal near hard stops to prolong the actuator's lifetime by not letting it crash into the hard stops. Tightening is a feature that increases the control signal when the wastegate is demanded fully closed to ensure that the wastegate is sealed. An initialization feature, auto-find limits, is also implemented. It does a sweep of all positions to find out where the hard stops are, and stores them.
3. A PI-controller was developed for the vacuum wastegate and tested in an engine test bench at different operating conditions. The PI controller is able to control the position, but with different results depending on whether the wastegate is closing or opening, this because of the different dynamics between opening and closing of the wastegate.
4. In this paper it is shown that, for accurate and fast control of the wastegate and with the use of well-known linear control design methods, the electric wastegate is preferred over the vacuum wastegate.
5. To accurately control the vacuum wastegate, the different dynamics depending on opening or closing of the wastegate need to be modeled and taken into account in the controller. For the closing of the wastegate, it was shown that it consists of two different phases, with the first phase doing a fast initial jump in position and the second one slowly reaching the desired position. It was also shown that the second phase was eliminated if the control signal saturates. Bringing this behavior into the controller is believed to be needed for a faster and more accurate control of the position. Hysteresis in the actuator system is also present.

## REFERENCES


1. Mehmood Adeel. Modeling, simulation and robust control of an electro-pneumatic actuator for a variable geometry turbocharger. Theses, Université de Technologie de Belfort-Montbeliard, November 2012.
2. Thomasson Andreas, Eriksson Lars, Leufven Oskar, and Andersson Per. Wastegate actuator modeling and model-based boost pressure control. In *IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling*, Paris, France,2009.
3. Thomasson Andreas, Leufvén Oskar, Criscuolo Ivan, and Eriksson Lars. Modeling and validation of a boost pressure actuation system for a series sequentially turbocharged SI engine. *Control Engineering Practice*, 21:1860–1870, 2013.
4. Glad Torkel and Ljung Lennart. *Reglerteknik, Grundläggande teori*. Studentlitteratur Lund, 2012.
5. Gustafsson Fredrik. *Statistical Sensor Fusion*. Studentlitteratur Lund, 2012.
6. Mehmood A., Laghrouche S., and El Bagdouri M.. Modeling identification and simulation of pneumatic actuator for {VGT} system. *Sensors and Actuators A: Physical*, 165(2):367 – 378, 2011. ISSN 0924-4247.doi:http://dx.doi.org/10.1016/j.sna.2010.11.006.
7. Gustafsson Fredrik, Ljung Lennart, and Millnert Mille. *Signal Processing*. Studentlitteratur Lund, 2011.
8. Ni Chunsheng, Xi Gangand, and Guo Hui. 涡轮增压器电动废气门精确开度控制的研究. *Shanghai Auto*, 8:28–32, 08 2013.
9. Nyberg Mattias and Frisk Erik. *Model Based Diagnosis of Technical Processes, Course Material in Diagnosis and Supervision*. Bokakademin Linköping, 2014.
10. Enqvist Martin, Glad Torkel, Gunnarsson Svante, Lindskog Peter, Ljung Lennart, Löfberg Johan, McKelvey Tomas, Stenman Anders, and Strömberg Jan-Erik. *Industriell Reglerteknik Kurskompendium, Course Material in Industrial Control Systems*. Bokakademin Linköping, 2014.
11. Holmbom Robin and Liang Bohan. Boost control with turbo speed sensor and electric wastegate. Master's thesis, Linköping University, Vehicular Systems, 2016.

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## 10. ABBREVIATIONS

**CUSUM** - Cumulative SUM

**EGR** - Exhaust Gas Recirculation

**EPC** - Electro-pneumatic Pressure Converter

**IMC** - Internal Model Control

**PWM** - Pulse-Width Modulation

**RPM** - Revolutions Per Minute

**SISO** - Single-Input Single-Output

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.



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