Multivariable Controller Design for Diesel Engine Air System Control

Important note: The due date is 24/11/2023. Late submission is absolutely not allowed as the grades have to be submitted to the department very soon after the final exam. You may work together with your classmates. But do write your report independently. And the results are supposed to be different from each other as the parameters are based upon your matriculation numbers.

1 Background

Over the past several years, government mandated regulations for diesel engine out emissions- specifically oxides of nitrogen (NOx) and particulate matter (PM) - for both on and off-road vehicles have become increasingly stringent, which is shown in Figure 1. This has resulted in many diesel engine manufacturers adding more complexity to the engine systems: more sensors to better measure and/or model what the engine conditions and emissions are at any given time as a function of operating conditions, and more actuators to allow for simultaneous control of additional variables and an increasing number of performance objectives.

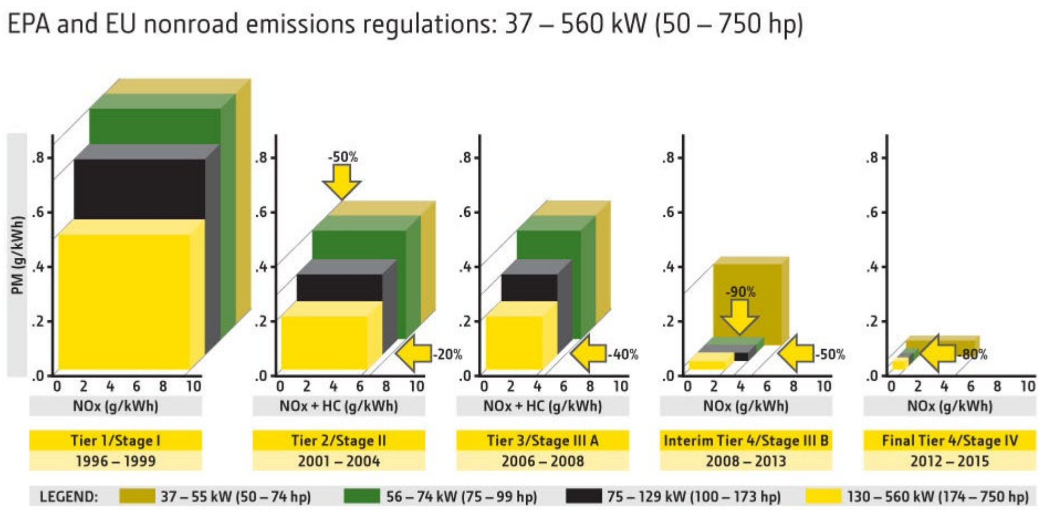

Figure 1 United States Environmental Protection Agency (EPA) emission standards [1]

As diesel engine emissions standards become increasingly stringent, one of the most commonly employed method of emissions reduction by engine manufacturers is active control of inducted air and recirculated exhaust gas (EGR). Commonly, actuators like EGR (Exhaust Gas Recirculation) and VGTs (Variable Geometry Turbochargers) are employed in order to manipulate the flow of gases through a diesel engine to achieve the desired reduction in NOx and PM emissions, as mandated by the US government other governments around the world. A diagram of a common air path layout involving this kind of control strategy is illustrated in Figure 2, where one can see the interactions and internal feedback caused by the EGR loop and turbochargers.

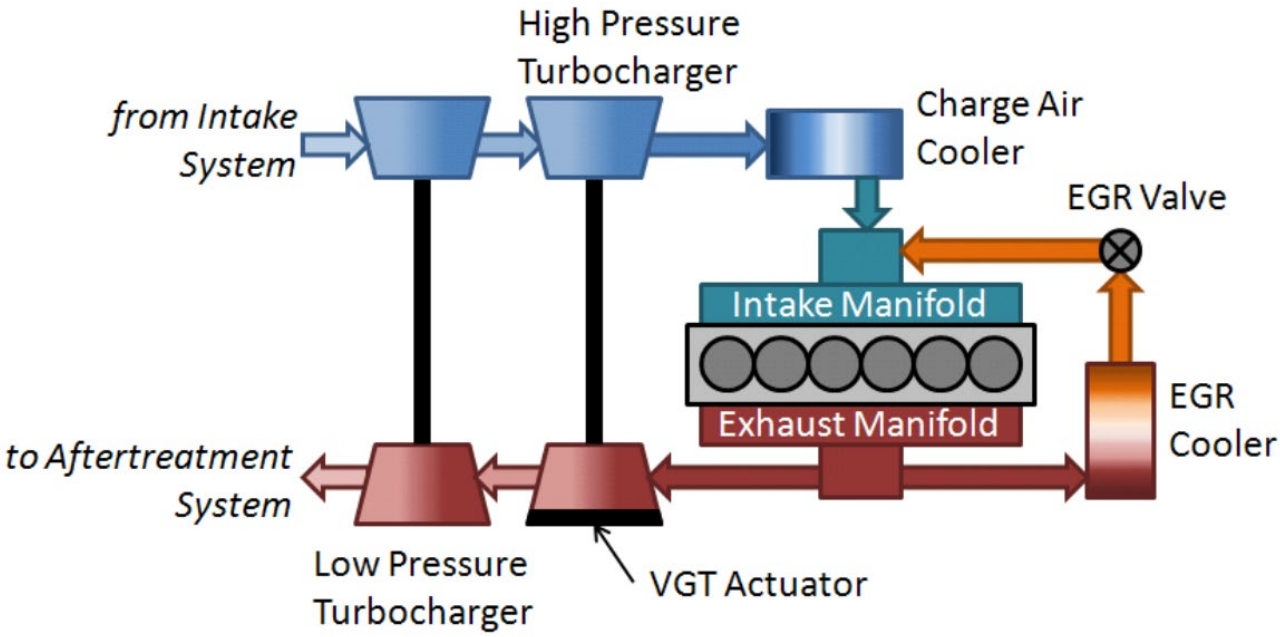

Figure 2 A typical diesel engine system diagram

In practice, the movement of either one of these actuators has a direct impact on the percentage of EGR in the intake manifold as well as the amount of air that can be inducted into the cylinder, resulting in a complex, interactive, multivariable system. Another difficulty of the engine air path control is to balance the engine's customer performance against the mandates of government agencies to reduce emissions, since the introduction of EGR into the air system has a negative impact on the overall fuel economy of the engine. In this mini project, we will model this engine air system as a MIMO linear system and try to control it using the techniques you have learned in *Linear Systems*.

This mini project is adapted from a Master thesis of Iowa State University [2]. To learn more details about the background of this project or the following modeling process, please refer to the complete thesis [2]. You can find its soft copy from NUS library.

2 Modelling

For model-based control, the first step is to build an effective dynamic model for our target plant, i.e., the engine air system in this project. Usually, there are two classes of methods to build a dynamic model, either by first principles or by system identification. For many complex process control applications, it is typically difficult, laborious, and time-consuming to derive a dynamic model from first principle equations. Besides, the acquired non-linear system also requires a significant time for calibration and verification, as well as more advanced control technologies.

Therefore, in the thesis [2], instead of developing a first principles non-linear state-space model of the engine air system, empirical data have been collected from the engine air system, and used to tune a linear fourth order state-space model using the commercially available System Identification Toolbox software of MATLAB. The linearization point selected is the Mode 1 engine certification speed/load operating condition, and this point was selected because it is the point that defines the engine's power rating. The detailed procedures to model this engine system through system identification can be found in [2]. Here we only give the obtained state space model,

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx, \end{aligned} \tag{1}$$

where the manipulated inputs $u = [u_1, \quad u_2]^T$ are the VGT Vane position VGT_{vane} and EGR valve position EGR_{valve} respectively, which as mentioned earlier are common actuators used on diesel engines for air system management and emissions reduction. The outputs $y = [y_1, \quad y_2]^T$ represent the in-cylinder air/fuel ratio (AFR) and intake manifold EGR percentage respectively. Please note that the outputs are not the ratios themselves. The output (or controlled) variables are proprietary modeled incylinder conditions, which correlate well to the previously mentioned in-cylinder air/fuel ratio (AFR) and intake manifold EGR percentage.

Since empirical input/output response data were used to identify the model, the matrices are therefore all full (i.e. all non-zero elements, which is usually not the case for first principles based models) and the states have no direct physical meaning (which is possible as state-space representations are not unique). The obtained system matrices are given as below

$$A = \begin{bmatrix} -8.8487 + \dfrac{a-b}{5}, & -0.0399, & -5.5500 + \dfrac{c+d}{10}, & 3.5846 \\ -4.5740, & 2.5010 * \dfrac{d+5}{c+5}, & -4.3662, & -1.1183 - \dfrac{a-c}{20} \\ 3.7698, & 16.1212 - \dfrac{c}{5}, & -18.2103 + \dfrac{a+d}{b+4}, & 4.4936 \\ -8.5645 - \dfrac{a-b}{c+d+2}, & 8.3742, & -4.4331, & -7.7181 * \dfrac{c+5}{b+5} \end{bmatrix},$$

$$B = \begin{bmatrix} 0.0564 + \dfrac{b}{10+c}, & 0.0319 \\ 0.0165 - \dfrac{c+d-5}{1000+20a}, & -0.02 \\ 4.4939, & 1.5985 * \dfrac{a+10}{b+12} \\ -1.4269, & -0.2730 \end{bmatrix}, \tag{2}$$

$$C = \begin{bmatrix} -3.2988, & -2.1932 + \dfrac{10c+d}{100+5a}, & 0.0370, & -0.0109 \\ 0.2922 - \dfrac{ab}{500}, & -2.1506, & -0.0104, & 0.0163 \end{bmatrix},$$

where a, b, c, d represent the last four digits in your matriculation number. For example, if your matriculation number is A0162903M, then $a = 2$, $b = 9$, $c = 0$, $d = 3$, and some parameters in (2) can be computed as follows

$$
\begin{aligned}
&2.5010*\frac{d+5}{c+5}=2.5010*\frac{3+5}{0+5}=4.0016,\\
&0.2922-\frac{ab}{500}=0.2922-\frac{2\times 9}{500}=0.2562,\\
&0.0165-\frac{c+d-5}{1000+20a}=0.0165-\frac{0+3-5}{1000+20*2}=0.0184.
\end{aligned}
\tag{3}
$$

Note that in the model (1), the four state variables x have no physical meaning since they are determined by system identification. Therefore, in reality these state variables cannot be measured directly. However, for the purpose of control system design practice in this mini project, we may assume the state variables can be measured with some sensors in specific questions of next part.

3 Control System Design

After all, we get a linear state space model (1) for the engine air system. In the following, different control strategies will be explored to achieve control of this system. We will target both the regulation and set point tracking problems. The initial condition for this system is assumed to be $x_0=[0.5,\ \text{-}0.1,\ 0.3,\ \text{-}0.8]^T$.

3.1 Design specifications

The transient step response performance specifications for all the outputs y in state space model (1) are as follows:

1) The overshoot is less than 10%.
2) The 2% settling time is less than 20 seconds.

Note: (a) This transient response is checked by giving a step reference signal for each input channel, i.e., [1, 0] and [0, 1], with zero initial conditions; (b) For all the following task 1) to 5), your control system should satisfy this performance specification and you are supposed to finish the required investigation for each task as well.

3.2 Tasks

Your study should include, but not limited to

1) Assume that you can measure all the four state variables, design a state feedback controller using the pole place method, simulate the designed system, check the step responses and show all the four state responses to non-zero initial state with zero external inputs. Discuss effects of the positions of the poles on system performance, and also monitor control signal size. In this step, both the disturbance and set point can be assumed to be zero. (15 points)
2) Assume that you can measure all the four state variables, design a state feedback controller using the LQR method, simulate the designed system, check the step responses and show all the state responses to non-zero initial state with zero external inputs. Discuss effects of weightings Q and R on system performance, and also monitor control signal size. In this step, both the disturbance

and set point can be assumed to be zero. (15 points)

3) Assume you can only measure the two outputs. Design a state observer, simulate the resultant observer-based LQR control system, monitor the state estimation error, investigate effects of observer poles on state estimation error and closed-loop control performance. In this step, both the disturbance and set point can be assumed to be zero. (15 points)

4) Design a decoupling controller with closed-loop stability and simulate the step response of the resultant control system to verify decoupling performance with stability. In this question, the disturbance can be assumed to be zero. Is the decoupled system internally stable? Please provide both the step (transient) response with zero initial states and the initial response with respect to x_0 of the decoupled system to support your conclusion. (20 points)

5) In an application, the operating set point for the two outputs is

$$y_{sp} = [0.4, 0.8]^T.$$

Assume that you only have two sensors to measure the output. Design a controller such that the plant (the diesel engine system) can operate around the set point as close as possible at steady state even when step disturbances are present at the plant input. Plot out both the control and output signals. In your simulation, you may assume the step disturbance of magnitude $w = [0.3, 0.2]^T$ takes effect from time $t_d = 10s$ afterwards. (20 points)

6) To make things more interesting, suppose we intend to regulate the four state variables directly instead of the two outputs. Our target is to maintain the states x around a given set point $x_{sp} = [0, 0.5, -0.4, 0.3]^T$ at steady state. Is it possible? In this question, you may assume all the state variables can be measured and there are no disturbances. (10 points)

   (a) If your answer is YES, please detail your control system design strategy to ensure x to be x_{sp} at steady state and demonstrate its effectiveness through simulation.

   (b) If your answer is NO, explain why. In such a case, we may only want to keep the state variables at steady state close enough to the set point x_{sp}. However, in practice, we usually place different emphasis on the exactness of the four state variables. To address our purpose quantitively, we aim to minimize the following objective function

$$J(x_s) = \frac{1}{2}(x_s - x_{sp})^T W (x_s - x_{sp}), \tag{4}$$

   where $W = diag(a+1, b+1, c+1, d+1)$ is a diagonal weight matrix and x_s is the state vector at steady state. Here, a, b, c, d are still the last four digits in your matriculation number, as defined above. Please detail your control system design strategy to minimize the objective $J(x_s)$ at steady state and demonstrate its effectiveness through simulation.

Note that there are no unique answers to all the above design questions. For the tasks in our project, you can assume that the control input is unlimited. However, in practice all the physical actuators can only provide a limited drive capacity. You need to make your own judgement assuming you are the engineer responsible for the control system design in the real world. There are three major factors you should consider when you design and justify your controller:

- Speed --- Transient response
- Accuracy --- Steady state error
- Cost ---- Size of the control signals

Please do follow the design procedures you have learned in *linear systems* to solve all the above questions. List the necessary formulas and intermediate results in your report. If you only call the MATLAB built-in functions for control system design with no details, for example, simply use *place* to place poles or *lqr* to design the LQR regulator, you will get ZERO marks.

4 Reference

[1] *Understanding Emission Regulations*. https://www.deere.com/en_US/services_and_support/engine-information/understanding-emission-regulations/understanding-emission-regulations.page.

[2] Humke, Daniel A. *Analysis of multivariable controller designs for diesel engine air system control*. Diss. Iowa State University, 2013.

5 Format of Reports

Your report should mainly contain the plant description, control and observer design method description, your design details, simulation results, possible comparison, comments and discussion, modification and refinements.

The report should include the following and be organized in the following sequence:

- A cover paper to indicate "Assignment for EE5101/ME5401 (or your specialization code if else) Linear Systems", a title of your report at your choice, your full name, your Matriculation number, email address and date;
- An abstract of 50-100 words on a separate page;
- A contents table on a separate page;
- Section 1 Introduction
- The major materials of your report organized nicely in a few sections each with specific focus. Label your equations, tables, and figures with number and caption for reference in the text. Your figure size and figure quality should be high enough to facilitate the verification of your results.
- The last section on conclusions.

- A list of reference books/papers if any;
- Appendices if any each on a separate page. Your MATLAB code should be in this appendix. If you use Simulink, a screenshot of your Simulink model should be inserted at proper position in the above major materials part as figures.

Pay attention to your presentation (English writing, organization, and layout et al). Make the report formal, complete and readable. It is also advisable to write your report with a word-processing software such as Word or LaTeX.

The final point to note about your report: it is the content that matters not the length. Keep in mind that there are only TWENTY SEVEN pages in John Nash's PhD thesis, which leaded to his Nobel Prize. Therefore, you will be penalized if you put too much "copy and paste" material in your report.

6 A Note on Access and Use of MATLAB

To complete the project, you are supposed to use SIMULINK and MATLAB. The easy way is to learn how to build various block diagrams in SIMULINK first, and then try to solve the control systems design for the mini-project. An excellent *Control Tutorial for MATLAB and Simulink* can be found at http://ctms.engin.umich.edu/CTMS/index.php?aux=Home. Besides, a Matlab manual is provided in CANVAS for the first timers.

If you don't have MATLAB on your PC currently, you can access MATLAB in either of the following two ways:

1) Go to PC clusters located at the third floor of E2: http://www.eng.nus.edu.sg/eitu/pc.html.
2) Download MATLAB from NUS information technology center: every NUS student can have a license. https://nusit.nus.edu.sg/services/software_and_os/software/software-student/#install-matlab.

Hint on MATLAB/SIMULINK:

A. You can use functions such as *step*, *initial* and *lsim* to simulate the system's corresponding response. Also, all these simulations can be done with SIMULINK.

B. In some cases, it may be easier to use SIMULINK for the simulation, for example, question 5).