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ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

# REVIEWER'S OPINION OF FINAL THESIS

## I. IDENTIFICATION DATA

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| **Thesis name:** | **Modeling and Control of Advanced Turbocharger System** |
| **Author's name:** | **Ankit Singh Rawat** |
| **Type of thesis :** | master |
| **Faculty/Institute:** | Faculty of Mechanical Engineering (FME) |
| **Department:** | Automotive, Combustion Engine and Railway Engineering |
| **Thesis reviewer:** | Ing. Lubomír Baramov |
| **Reviewer's department:** | Honeywell Transportation Systems, Connected Vehicle |

## II. EVALUATION OF INDIVIDUAL CRITERIA

| **Assignment** | **challenging** |
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The main part of the assignment is, first, to review turbocharger technologies. Next, to develop a mean-value model of a turbocharged engine suitable for model-based control, and subsequently, to perform a sensitivity study with respect to a possible turbocharger degradation, which is relevant to vehicle health monitoring. Finally, extend the model involving a classical waste-gated turbocharger to the combination of this turbocharger and electrically powered compressor (e-charger) and to perform an analogous sensitivity analysis. Air-path modelling is a non-trivial task because of inherent model stiffness.

| **Satisfaction of assignment** | **fulfilled** |
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Student fulfilled all points of the assignment.

| **Method of conception** | **correct** |
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Student used standard approaches of mean value modelling of the engine air-path for the use in real-time control. He had to choose an appropriate level of complexity and tackle problems of stiffness to get a robust and efficient simulation

| **Technical level** | **D - satisfactory.** |
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*Assess level of thesis specialty, use of knowledge gained by study and by expert literature, use of sources and data gained by experience.*

Student had to learn modelling approaches of air-path model components, approximating turbine and compressor maps by functions and building the air-path model with boost control. The modelling approaches are standard and described in the thesis. Only one of the component models – the intake manifold – is not adequately described in Section 4.7.2; the relation of formula (4.7.2.1) to the text in paragraph 4.1.1.4 is not obvious and there is a unit inconsistency. The following formula (4.7.2.2) is not commented at all.
The main results are in chapters 6 and 8. Chapter 6 contains multiple simulations with different trajectories of desired manifold pressure and engine speed, representing specific vehicle maneuvers. Here I miss a note of the boost control strategy (I assume it is a PID controller). Each simulation case is accompanied by a number of plots; I would prefer to include also the fresh air mass flow, and possibly also the turbine / waste-gate flows, to get the full picture. The turbine outlet pressure is clearly correlated with the waste-gate position, which is not consistent with (4.6.1) – this fact deserves an explanation. Further, a sensitivity study with respect to various turbocharger degradation follows. The degradation is simulated by changes in turbocharger maps; in addition to the verbal characterization of '5%, 10% of flow/ efficiency degradation', it would be appropriate to plot modified maps. The interpretation of the sensitivity results is a little confusing. First, the term 'degraded' is used not only for the hardware part (turbine or compressor) or its model (map), but also for variables as mass flows, rotational speed and so on, where it is used instead of 'decreased'. In the description of Graph 13(a) it is written *'…turbo-speed gets degraded…'*. However, Graph 13(e) does not show any noticeable difference in turbo-speed for cases under investigation. Similar confusion appears at multiple places.
The following chapters deal with the air-path involving a cascade of a conventional waste-gated turbocharger and a compressor driven by an electric motor. Sometimes it is not clear whether the term '*e-charger*' refers to the electrically powered compressor or to that cascade. The map for the electrical compressor is not plotted (is it the same as that of the turbocharger's?). Section 7.2. should describe the boost controller. It lists its subsystems without describing their principle and the control objective. The layout in Fig 24 omits the feedback to Kalman filter and there is also an inconsistency between the output of the LQ controller as the reference for the inner control loop with a PID controller and the controlled value. On

several occasions, instead of 'LQ controller', the term 'LQ function' is used. Chapter 8 then contains similar set of simulations as in Chapter 6 for the classical turbocharger. However, some variables are not plotted, as electrical compressor speed and pressure at its outlet, turbine/e-charger power, which would be useful for understanding the load allocation between the turbocharger and e-charger. Some questions arise when compared the case of Section 8.1.1 to the case with a classical turbocharger in Section 6.1.1: Why the pressure difference between compressor outlet and intake manifold is much larger in the case of the turbo-charger? When the intake manifold pressure is the same and the engine speed is the same, the engine/ compressor flow should be nearly the same, and so should be the pressure difference across the intercooler. Also, why is the waste-gate significantly more open in the e-charger case for the same speed/ boost demand? As for the sensitivity study, the setting in 8.2.1. for 0% degradation should be the same as in 8.1.1; nevertheless the plots are different. Is it because of a different controller tuning?

**Formal and language level, scope of thesis** **E - sufficient.**

The formal level of the thesis is not good. The notation list is not in alphabetical order, with some duplicities; F/A is incorrectly explained as fuel heating value. Section 2.2 – contains citations of multiple sources with unnecessary repetitions of some equations. The presentation is not clear and difficult to follow. In the simulation cases, the individual plots are not clearly labeled with plotted variable; that information must be looked up in the subsequent text, often with wrong cross-references.

**Selection of sources, citation correctness** **D - satisfactory.**

The student used the most influential sources in engine mean value modelling, including the handbook by Heywood, Book by Guzzella and Onder, paper by Jensen, Kristensen et al. The author cites other references in the thesis as e.g. sources for figures, but not in the Reference list, which should have been done. The references in the list are sufficient to do the work, although there are more papers available on steady-state turbine compressor modelling, approximating their maps. The student made an effort to distinguish his work from other sources, I cannot see a breach of ethics.

## III. OVERALL EVALUATION, QUESTIONS FOR DEFENSE, CLASSIFICATION SUGGESTION

The author dealt with a difficult topic. He had to gain knowledge from multiple areas as turbine/ compressor modelling, ideal gas law and thermodynamics, model calibration, control and simulations and achieved highly useful results. However, the overall presentation is not good, the thesis is difficult to follow and contains some inconsistencies. I would ask the student to provide at the defense a detailed presentation of one e-charger case (response to the boost demand case and constant speed) with additional plots mentioned in the Technical level paragraph above, and comparing it to the conventional turbocharger.

I evaluate handed thesis with classification grade **D - satisfactory.**

Date: **3.9.2018** Signature: