PHD THESIS EVALUATION REPORT

Thesis title: **Model Identification for Advanced Tunnel Ventilation Control**

Author: **Ing. Jan Šulc**

The thesis focuses on development, refinement and application of mathematical models of airflow dynamics in road tunnels of complex structure with forced ventilation and their use for control design. The emphasis is laid on design of localised ventilation control during fire situations, when the dynamics play important role. On the other hand, static flow and pressure balance over the tunnel main body and its branches is important for the control system at normal situation. In this latter case also solved in the thesis, handling the MIMO character and complexity of the problem is the main challenge.

The thesis is formed as a *commented selection of published results*, three journal papers to be more specific. Having three journal papers published as the first author may be considered as a very positive aspect of research work by the author. However, none of the papers is presented in a top journal in the *Automation and Control Systems* category. With no doubts, the thesis presents a wide range of original and very interesting results. It is also clear that a lot work has been done by the author in the subject, which is still wide open. On the other hand, some of the selected approaches are questionable, as will be discussed further on in more detail. A negative aspect of the thesis is in very brief comments to the papers. The contribution of the author should be described more specifically. Such wider comments and discussion should especially be more detailed for the third paper presenting an optimization based control system design of a tunnel complex, implemented and tested in Blanka tunnel. This must have been work of a broader team. It is not clear whether the claimed 75% authorship is aimed just for theoretical and experimental aspects of the work, or whether it is the contribution of the author to the overall control system design. Besides, control design details omitted namely in the first journal paper due to rather applicable journal scope could have been provided in more detail via the comments. Instead of additional valuable information, various unnecessary statistics on the journals are given. Then an abstract-like summary and brief text on contribution to fulfilling thesis goals are presented for each of the journal papers.

The composition of the thesis structure is not well chosen. After two-page introduction, goals of the doctoral thesis are outlined. After that, state of the art is given. The thesis goals should be derived based on proper analysis of state of art, revealing research gaps to be filled. Better and more logical structure would then be: Introduction – State of the art – Thesis goals.

The thesis aims at fulfilling four goals which can be briefly outlined as:

1. Compose state space model of airflow dynamics for road tunnels.

2. Propose and validate a systematic procedure for airflow velocity control during fire situations in tunnels

3. Propose ventilation control system for normal operation in road tunnels following a number of constraints and the goal to minimize the energy consumption.

4. Propose an algorithm for compensation of airflow model based on measurements.

The first goal is solved in the first paper presented in Section 4.1, which was published in "Tunnelling and underground space technology" journal. This objective can be considered as preliminary. Its solution is based on applying known physical relations (extended Bernaulli and continuity equations, etc.) to form a state space model of the complex system at hand – a road tunnel under fire situation. To simplify the model, the balances are made in one dimension only. This assumption is reasonable to avoid extensive complexity of the overall model. On the other hand, the inertia effect of the turbulent air motion exerted by the fans mounted at the tunnel ceiling could have been better represented in the model. The fan cannot act as an ideal piston. The velocity responses to the fan supply change should be of higher order dynamics. Neglecting this dynamics most likely causes considerably shorter dead-time in simulation results compared to measurements in Fig. 15. Despite the composition of the model is a rather methodical work, the author deserves credit for the precision and explanation of the whole procedure. Though, the contribution to the applied control theory of this paper is rather moderate. It is just mentioned that the PID, implemented in the very basic form, is tuned by simulations. From the practical point of view, the contribution can be found in spreading the control action to activation of available fans, most of which are controlled in on/off regime. This method is described more extensively in the second paper given in Section 4.2. A positive aspect is also in experimental validation of the given model and control design methodology.

The second goal is solved in section 4.2 presenting the paper published in "Control engineering practice". After a general introduction, the 1-D model presented in the previous paper is outlined and extended. For proposing the systematic control design procedure, SIMC (Skogestad IMC) method is applied. The SIMC method for tuning PI(D) controllers based on step response test is very practical for processes with a distinct dead time, when the model is not available. In literature, it is also referred that the method can be used as a model order reduction technique based on matching the step responses of the original model and the first order plus dead time model. However, such an order reduction technique is risky if the original model is of a complex nonlinear structure, as it is here. It is mainly due to the fact that some of the dynamical modes can be neglected in this approximation.

The proposed tuning method is formed as follows: First, the complex nonlinear model is derived. Then, it is approximated by the first order plus dead-time model at a given section and for given operational point. Its gain, time constant and delay are then turned to PI parameters by the SIMC rules. As mentioned above, application of this method would be useful if the parameters were to be tuned directly from the measured responses. But parametrizing approximation of a complex nonlinear model just based on a step response is not a proper approach, in my opinion. The other characteristics, e.g. frequency responses, can substantially differ between the original and approximate models. Turning the multi-parameter model to three parameter approximate model would make better sense, if the parameter uncertainties were taken into account. Unfortunately, it is not the case here. It is also mentioned, that originally, root-locus method was applied to tune the controllers. In my opinion, the root locus is a better tuning tool than the SIMC method if the model is available. When applying the approximation by SIMC, some faster modes (seen in the root-locus) can be omitted, which can decrease stability margin or even destabilize the closed loop. A very positive aspect of the paper is a comparison of simulation results with true measurements. The paper is also very well written and easy to follow. Unfortunately, I cannot agree with the conclusion of the paper claiming that SIMC method is very suitable for the given application.

The last two objectives are then solved in the third paper published also in "Control engineering practice", and given in Section 4.2. In my opinion, this paper alone (of award quality) qualifies the author to receive PhD. Unlike in the previous papers aimed at handling the fire events, static balance model of Blanka tunnel is formed and used for feedforward control design. After forming the model, the control system architecture is introduced, including a state switch for various operational modes. Due to involvement of many control actuators and airflow velocities in the segments to be handled, the problem is of extensively complex nature. The complexity even grows if the requirement on minimal energy consumption together with various constraints are taken into account. The problem is elegantly simplified by definition of slack variables – velocity set-points - allowing to relax constraints on the airflow velocity in the tunnel segments. The arising constrained non-convex optimization task is then solved by Sequential quadratic programming.

The significant contribution of the third paper is also in proposing a method to compensate differences between the model results and measurements. It is done by defining an adaptable parameters in the continuity and pressure equations. The parameters are continuously adjusted based on measurements using least squares algorithm with exponential forgetting. The improvement of the model performance is well demonstrated against the measurements. A unique aspect of the paper is validation of the theoretically proposed methodology on long term operation in Blanka tunnel. This includes also discussion on gradual improvement of performance, starting from basic algorithm, to feed-forward control without and with the adaptation. The paper also includes discussion on further steps, e.g. application of method to search for a global optimum. The thesis is concluded by discussion on fulfilment of the goals and chapter with conclusions and future work.

The results presented in the thesis clearly show that the author is an independent researcher with wide and complex research abilities that cover: i) assembling models of enhanced structure, ii) applying advanced control design tools, iii) bringing the designed control methods to applications, and iv) evaluating the complex process measurements. Despite my critical note to the second paper, which can further be discussed, I recommend the thesis for defence.

Questions for the defence

1. In section 3.3 of the first paper, it is mentioned that fixed step explicit Euler method was applied for simulations. This can be very risky for the complex nonlinear model concerning both accuracy and even stability. What was the purpose for selecting this option? A standard choice should be to use a method with step adaptation, preferably semi-implicit.

2. In comparison of measured and simulated responses in Fig. 15 of the first paper, and also in some other responses, the dead-time of the measured response is considerably longer than the dead time of simulated response. In my opinion, it is given by neglecting the inertia of the air motion in response to fan performance. Including additional sub-models approximating this dynamics could bring better results. Have you considered this type of model adjustment?

3. Please, explain the background for choosing approximation of the dynamics by first order plus dead-time model in the second paper. If the process model is available, a standard model reduction method could be used, followed by application of analytic or optimal control design

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tools. SIMC method, which I fully acknowledge as a nice tool for practitioners, would be a reasonable choice if you want to parameterize the controller just based on measured step responses. Besides, have you thought of considering parameter uncertainties and robust controller design? This would be a reasonable choice taking into account the nonlinear character of the system and the dependence of the responses on selected operation point and control action magnitude.

4. It is not clear how the approximate models in the form (18) were parametrized. Was it really by simulating the step responses of segment models?

5. Why simple PI controllers were used in the second paper? Much better performance could be achieved even with PID controllers with proper filtration of the derivative part. The antiwindup solution is also rather basic. Are the HW constraints of the control system behind this?

6. For the third paper, please include more details on your 75% authorship.

7. Have you progressed with the solution of the optimization task outlined in the last paper? Could possibly some recent methods, such as GRANSO be applied? During the long term operation, was the optimization problem found always feasible? Has a really critical situation been faced during control system operation?

In Prague, March 12, 2019

prof. Ing. Tomáš Vyhlídal, Ph.D.

Department of Instrumentation and Control Engineering,
Faculty of Mechanical Engineering,
and Czech Institute of Informatics, Robotics and Cybernetics,
Czech Technical University in Prague