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A systematic approach for airflow velocity control design in road tunnels

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ABSTRACT

This paper introduces a systematic approach to design and tune the airflow velocity control system for use during fire situations in road tunnels. The proposed approach is focused on road tunnels with a complex structure; long tunnels with connected ramps (entrances and exits), where the controller design can be challenging and time consuming. Such tunnels usually have many sections where a fire can be localized, and this makes the control task difficult. Our approach is based on a simplified one-dimensional simulation model of a tunnel, which includes all the important factors influencing the airflow dynamics of a tunnel. The proportional–integral (PI) controllers are tuned based on the Skogestad Internal Model Control (SIMC) method, which requires a simple model for the process dynamics. The case study is the airflow velocity control in the Blanka tunnel complex in Prague, Czech Republic, which is the largest city tunnel in Central Europe. The results of the paper show how to improve the control algorithm in real operation and how to use the proposed systematic approach for future tunnels.

1. Introduction

Airflow velocity control during fire situations in road tunnels is critical for several reasons (Sturm, Beyer, & Rafiei, 2015):

- to provide suitable conditions for evacuation,
- to support rescue and fire-fighting operations,
- to prevent damage to tunnel installations.

Tunnel ventilation designers have learned a lot from fires in road tunnels that occurred at the turn of the century; Mont Blanc Tunnel (39 fatalities), Tauern Road Tunnel (12 fatalities), St. Gotthard Tunnel (11 fatalities) and Gleinalm Tunnel (5 fatalities), and now invest in safety equipment, especially fire ventilation elements (PIARC, 2011a).

The main aim of the airflow velocity control during fire in road tunnels is to ensure safe smoke propagation, which means to control the longitudinal airflow velocity. In city tunnels, there are often congestion and stop-and-go situations, and in case of fire, there can be blocked vehicles on both sides (upstream and downstream) of the fire source.

If the longitudinal airflow velocity is about 1.2 m/s, the smoke stays under the ceiling of the tunnel in a separate layer from the fresh air, which extends the time for evacuation (PIARC, 2011b).

In order to support rescue and fire-fighting operations, the desire is to extract all smoke from the tunnel. In such cases, the longitudinal airflow velocity should be higher than the critical velocity in order to avoid smoke propagation against the direction of airflow. The critical velocity depends on many factors, such as heat release rate of fire, cross-section area of the tunnel, slope of the road, etc., and the exact value can be determined based on detailed Computational fluid dynamics (CFD) simulations. Typical values for critical velocity are in the range of 2.2–3.5 m/s (Sturm et al., 2015).

How should we control the longitudinal airflow velocity and which is the most suitable control algorithm? In road tunnels, usually several control techniques are used; some algorithms are closed-loop with various logic elements (Espinosa, Fernández, Del Ray, & Alarcón, 2010) and some of them are feed-forward due to unreliable measurements of airflow velocity (Pospisil & Brandt, 2005). The most recent published paper (Euler-Rolle, Fuhrmann, Reinwald, & Jakubek, 2017) introduces nonlinear feed-forward control with the feedback model linearization. Results of this paper are demonstrated by its application to an Austrian highway tunnel. PI controllers are used for the vast majority of industrial processes (Visioli, 2011). Derivative action is normally not included, as it usually has a minor effect on performance and requires filtering of the measurement. Most industrial Programmable logic controllers (PLC) have a standard block for implementing the PI controller. Although the PI controller has only two parameters for tuning, it is still difficult to

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find the proper values of the proportional gain and the integral time constant. Unfortunately, a lot of engineers still use trial error methods, which in many cases result in poor tuning.

There exist several PI design methods. The classical Ziegler–Nichols method is generally rather aggressive and does not have an adjustable tuning factor. Moreover, this method often requires experiments with oscillations, which could have serious consequences for the controlled process. An analytically based method, Internal Model Control (IMC), was introduced by Rivera, Morari, and Skogestad (1986). It gives good results for set-point changes, but it does not have a good disturbance response for integrating processes. Skogestad improved this method to get a good response also for integrating processes. This method is known as the SIMC tuning method (Skogestad, 2003).

The aim of the paper is to propose a simple systematic procedure for how to design and tune the PI controllers for ventilation airflow velocity. The case study is the airflow velocity control system in the Blanka tunnel complex in Prague, Czech Republic. Originally, the PI controllers of the ventilation airflow velocity in the Blanka tunnel complex were tuned using the root locus method based on knowledge of the process dynamics. Nevertheless, it cannot be considered as a systematic procedure. In practice the root locus is more ad hoc, because there are many tuning parameters and no simple tuning guidelines. The paper shows how to design the PI controllers for a complex tunnel system using a systematic procedure, the SIMC method, which is probably the best simple tuning method for proportional–integral–derivative (PID) control. The results of the paper are recommendations and suggestions for improvements of existing airflow velocity control system for real operation of the Blanka tunnel complex. The suggested approach can be also used in the future for the design of airflow velocity control system in other complex tunnels.

2. Case study: the Blanka tunnel complex in Prague

2.1. Basic characteristics of the tunnel

The Blanka tunnel complex in Prague forms the north-west part of the Prague City Ring Road and represents the largest road tunnel complex in the Czech Republic. It is a tunnel complex, which means, it consists of three road tunnels; Bubeneč, Dejvice and Brusnice, which are connected together through tunnel crossroads (ramps); see Fig. 3. It is a double tube tunnel with unidirectional traffic in each tube and the total length of the tunnel is approximately 5.5 km. The route passes the urban development and partially also the historical center of Prague and the average traffic intensity is about 60 000 vehicles per day (altogether in the whole tunnel) (Satra s.r.o., 2016).

2.2. Fire ventilation system

The fire ventilation system of the Blanka tunnel is longitudinal with transverse extraction of smoke. In most of the tunnel sections, smoke is extracted with controllable dampers (valves, which regulate the airflow inside the duct) and further through fans in ventilation machine rooms and stacks from the tunnel to the outside environment. In sections that are located within, or close to the exit ramps, the smoke is extracted longitudinally. A schematic illustration of smoke extraction in case of fire is depicted in Fig. 1.

There are five ventilation machine rooms intended for smoke extraction; Trója, Letná, Špejchar, Střešovice and Prašný most. The ventilation machine rooms are equipped with axial fans with variable speed, see Fig. 2.

The longitudinal airflow is controlled by 88 jet fans. The jet fans are located in couples or triplets at the ceiling of the tunnel, see Fig. 4. Some of them are equipped with variable speed drives, which allow continuous regulation of speed, however the majority of the jet fans can be controlled only by start/stop (they are equipped with soft-starters). All the jet fans are fully reversible, which means that they can either support airflow velocity in the traffic direction or, if necessary, to brake the airflow velocity.

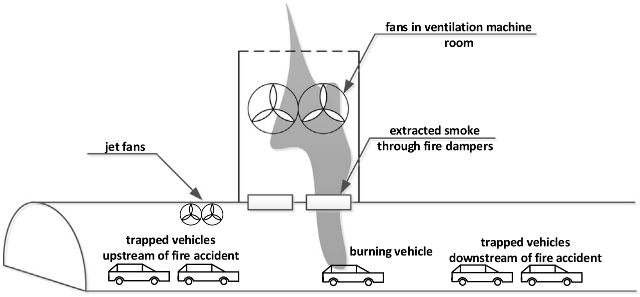

Fig. 1. Smoke extraction through controlled dampers and fans in ventilation machine rooms during fire situations.

Fig. 2. Ventilation machine room Letná including three axial fans for smoke extraction from the tunnel (2015) (Karlíček, 2016; Satra s.r.o., 2017).

There are three independent sensor systems for fire detection. The primary source for fire detection is a linear heat detector, which is an optical cable that detects increased temperature. The other sensors are smoke detectors and closed-circuit television (CCTV). Together, there are 125 detection sections (marked as SM1-SM125), where a fire can be localized. The length of each section is about 80 m.

After the confirmation of a fire, there are two stages of fire ventilation using the PI controllers of airflow velocity. The manipulated variable (u) are the jet fans in the tunnel and the controlled variable (y) is the longitudinal airflow velocity upstream of the fire location. The aim of the first stage, the evacuation stage, is to control the longitudinal airflow velocity, and the set-point value is 0.9–1.6 m/s (depending on the location of the fire). In the second, fire-fighting stage, the set-point value is increased to 1.9–3.6 m/s (critical velocity), in order to avoid smoke propagation against fire-fighters.

The set-point values are determined based on CFD simulations and they depend on cross-sections area of the tunnel and road gradient (declining sections need higher set-point values to avoid smoke propagation against the traffic).

3. A systematic procedure for airflow controller design

We here describe a systematic procedure for the design of the airflow velocity control system in a road tunnel based on simple PI controllers. The fire ventilation system is activated in the detection section where the fire occurs. In the Blanka tunnel complex, there are 125 detection sections, which means that up to 125 different PI controllers need to be designed. Fortunately, many sections are similar, which reduces it to about 23 controllers. In this paper, we discuss two of these controllers. We do not here discuss the fire detection system (see Šulc, Ferkl, Cigler,