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Longitudinal tunnel ventilation control. Part 1: Modelling and dynamic feedforward control

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ABSTRACT

Road tunnels exceeding a certain minimum length are equipped with a ventilation system. In case of a fire it is used to achieve a predefined air flow velocity in the tunnel by adequately controlling the installed jet fans in order to ensure sufficient visibility for persons to safely follow the escape routes. As the dynamics of the air flow in road tunnels strongly depend on the tunnel length, short tunnels with longitudinal ventilation systems pose a challenging control task. In this paper, non-linear dynamic feedforward control is proposed for longitudinal ventilation control in case of an emergency. For this purpose, an analytical non-linear zero-dimensional model of the air flow is feedback linearised. Due to its special properties, which are presented and analysed, two different versions of feedforward control are proposed: One is focused on performance, the other on robustness. Finally, the beneficial behaviour of the presented two-degrees-of-freedom control approach is demonstrated by its application to an Austrian motorway tunnel.

1. Introduction

New constructions or refurbishments of road tunnels impose increasingly tight safety requirements on the electrotechnical tunnel equipment such as the ventilation system, as well as on its operation. Particularly in the event of an incident with fire and smoke spreading in the tunnel, adequate safety measures have to be taken without delay to protect life and health of the tunnel users. The main goal is to guarantee a minimum amount of time for persons in the tunnel to safely follow the escape routes with sufficient visibility available. For this purpose, tunnels exceeding a certain minimum length are equipped with ventilation systems. There exist several, very different approaches to ventilation concepts (Sturm, Beyer, & Rafiei, 2015; PIARC, 2011; Bendelius, 1996). In this paper, longitudinal ventilation is considered in case of an emergency, where jet fans are used to induce fresh air into the tunnel through one portal and exhaust the smoke through the other. However, since the spread of smoke in the tunnel can not be measured in tunnels with longitudinal ventilation, it is assumed that a safe condition is achieved by maintaining an average air flow velocity in the tunnel, which is high enough to convey smoke out of the tunnel, but not too high to save the naturally occurring smoke stratification from being destroyed. Thus, appropriate and accurate jet fan control is critical to achieve a satisfactory control performance and provide the opportunity for persons to escape safely, respectively. In this context, control is especially challenging for short tunnels due to their low inertia and the resulting highly dynamic behaviour. In shorter tunnels, the overall air mass located within the tunnel is lower, which leads to a more imminent effect of any momentum source (from jet fans or disturbances) on the rate of change of the air flow velocity.

In combination with tight trajectory tracking requirements, actuator saturation and the need to avoid undesired overshoot of the air flow velocity, a non-linear control scheme should beneficially be used to control the jet fans taking into account non-linearities of the jet fans as well as of the non-stationary Bernoulli equation as the tunnel air flow model. Especially as there are several disturbance influences such as vehicles in the tunnel, buoyancy of hot gases, wind load onto the portals or meteorological pressure differences influencing the flow velocity, an appropriate reference tracking as well as sufficiently fast disturbance rejection are required.

Usually, tunnel ventilation systems are controlled by standard linear feedback controllers such as PI or PID controllers. However, these conventional control schemes reach their limits of applicability as soon as non-linear effects become increasingly dominant. On the one hand, a tradeoff between reference tracking performance and disturbance rejection capability has to be made in the controller tuning. On the other hand, as the non-linear effects grow stronger and the system state lies further away from the plant linearisation point, the closed

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Nomenclature

List of variables

$A_{\mathrm{JV},i}$	cross sectional area of jet fan i
A_{Tunnel}	cross sectional area of the tunnel
c	abbreviation defined in (34).
$d(\boldsymbol{x})$	thrust distribution function/algorithm
D_{hydr}	hydraulic diameter of the tunnel
$\boldsymbol{e}$	model error vector in the parameter optimisation
$\boldsymbol{f}$	system dynamics of the state space model
$\boldsymbol{g}_i$	affine input function of input i of the state space model
h	output function of the state space model
$k_{\mathrm{e},i}$	installation factor of jet fan i
k_{Fric}	overall friction coefficient
$k_{\mathrm{JV},i}$	thrust coefficient of jet fan i
L	tunnel length
$\mathcal{L}$	cost function in the parameter optimisation
$\mathrm{L}_{\boldsymbol{f}} h$	Lie derivative of h along vector field $\boldsymbol{f}$
n	state space system dimension
n_{JV}	number of installed jet fans
n_{on}	number of jet fans fully switched on
n_{s}	dimension of model error vector $\boldsymbol{e}$
Δp	equivalent pressure difference
r	relative degree
$\boldsymbol{R}$	weighting matrix in the parameter optimisation
$R(\boldsymbol{x}^*, n_{\mathrm{on}})$	abbreviation defined in (38).
$\mathcal{T}$	diffeomorphism from $\boldsymbol{x}$ to $\boldsymbol{z}$
u	air flow velocity
u_{m}	air flow velocity measurement
u^*	feasible air flow velocity
u_{m}^*	feasible air flow velocity considering measurement dynamics
v	virtual input to the external dynamics
$v_{\mathrm{JVmax},i}$	maximum average outlet velocity of jet fan i
w	air flow velocity reference
$\boldsymbol{x}$	state vector
$\boldsymbol{x}^*$	required state trajectory associated with w
${}^{+}x_2^*$	req. trajectory of x_2 associated with w (solution 1)
${}^{-}x_2^*$	req. trajectory of x_2 associated with w (solution 2)
y	output of the state space system
$\boldsymbol{z}$	state vector of the transformed system
$\boldsymbol{\Delta}$	disturbance input of the state space system
λ	wall friction coefficient
ω_i	dimensionless rotational speed of jet fan i
ω_{dmd}	dimensionless rotational speed reference
ω_{dmd}^*	dimensionless rot. speed ref. from feedforward control
${}^{+}\omega_{\mathrm{dmd}}^*$	rot. speed ref. from feedforward control (solution 1)
${}^{-}\omega_{\mathrm{dmd}}^*$	rot. speed ref. from feedforward control (solution 2)
ω_{v}	virtual rotational speed of a single substitute jet fan
ω_n	undamped natural angular frequency of the ref. generation
$\boldsymbol{\Psi}$	weighting matrix in the parameter optimisation
ρ	air density within the tunnel
$\boldsymbol{\theta}_0$	initial parameter vector in the parameter optimisation
$\Delta\boldsymbol{\theta}$	parameter vector deviation from $\boldsymbol{\theta}_0$
$\tilde{\Sigma}_{\mathrm{ol}}$	open loop plant model
$\tilde{\Sigma}_{\mathrm{ol}}^{-1}$	inverse open loop plant model
Σ_{m}	measurement dynamics
$\tilde{\Sigma}_{\mathrm{m}}$	model of the measurement dynamics
Σ_{C}	feedback controller
σ	step signal applied in the ref. generation
τ_{JV}	time constant of the jet fan thrust buildup
τ_{m}	time constant of the measurement dynamics
ζ_{E}	factor describing influx losses in the friction coefficient
ζ	damping ratio used in the ref. generation

loop performance decreases. When non-linear feedforward control is used as an extension of standard feedback control, a feedback controller tuning specific to disturbance rejection can be applied. Thus, an improved closed loop performance is achieved across the whole operating range.

In advanced and non-linear control schemes, the application of feedforward control is state of the art. Usually, a dynamic feedforward control law is obtained by some kind of model inversion. Whereas most applications are based on a design using feedback linearisation (Hagenmeyer & Delaleau, 2003), system inversion still remains a challenging task. For that reason, a profound analysis and knowledge of the non-linear system under consideration is required. Applications of feedforward control can be found in a variety of fields, such as for example the actuation of hydraulic automotive clutches (Horn, Bamberger, Michau, & Pindl, 2003), temperature control of industrial processes (Malchow & Sawodny, 2012) or the gas supply of fuel cells (Danzer, Wilhelm, Aschemann, & Hofer, 2008).

In the literature, advanced control methodologies for tunnel ventilation have been mainly proposed for normal tunnel operation only. In contrast to emergency ventilation, the main goal in normal operation is to comply with restrictions imposed on the opacity, as well as on the concentrations of air pollutants within the tunnel such as $\mathrm{NO_x}$ or CO. Several control strategies have been applied in combination with different model configurations. Hrbcek, Spalek, and Šimák (2010) combine model predictive jet fan control with autoregressive moving-average models describing the pollution concentrations. Kurka, Ferkl, Porízek, and Jul (2005) as well as Ferkl and Meinsma (2007) use a model, which is split into submodels with different one-dimensional spatial discretisations to simulate traffic, ventilation and pollutant concentrations. The simulation is performed on a car by car basis and the effect of ventilation is considered by the steady-state Bernoulli equation. Tan et al. (2012) performed 3D CFD simulations of pollutant levels and extracted step response features from the data to apply dynamic matrix control. Also fuzzy models have been applied several times for prediction and simulation of pollutant concentrations (Chen, Lai, & Lin, 1998). Bogdan, Birgmajer, and Kovačić (2008) developed a static feedforward control for the number of necessary jet fans and combined it with fuzzy control to meet the air quality limits. Based on the prediction of the required air flow (depending on traffic and weather conditions), the number of currently required jet fans is found from the steady-state Bernoulli equation based on an estimated tunnel air speed necessary to supply the required air mass flow. In contrast to the proposed model-based dynamic feedforward control, Bogdan et al. (2008) consider the pollutant levels only and no dynamic behaviour of the air flow velocity is considered. In normal operation, in addition to the achievement of appropriate pollutant levels, also the minimisation of power consumption has been demonstrated by fuzzy predictive control (Karakas, 2003) or genetic algorithms in combination with fuzzy control (Chu et al., 2008). However, all these contributions deal with normal tunnel operation only and do not consider the dynamic behaviour of the air flow velocity.

Emergency ventilation has been treated by Nakahori, Mitani, and Vardy (2010) in a simulation study using an encompassing automatic control system for long two-way road tunnels with longitudinal ventilation. However, the focus is rather on overall control system considerations than on the specific feedback and feedforward control design.

In the present paper, model-based non-linear dynamic feedforward control is applied to the longitudinal tunnel ventilation to enhance standard feedback control and improve the closed-loop behaviour. The