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Characteristics-based model predictive control of selective catalytic reduction in diesel-powered vehicles

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ABSTRACT

In heavy-duty diesel exhaust systems, selective catalytic reduction (SCR) is used to reduce NO_x to nitrogen to meet environmental regulations. Diesel exhaust after-treatment involves a set of components that are best characterized as distributed parameter systems. Thus, the optimal ammonia dosage in the SCR is an important and challenging problem in diesel exhaust treatment. In this work, we propose a method to synthesize an optimal controller for the SCR section of the diesel exhaust after-treatment system, which is based on a system model consisting of coupled hyperbolic and parabolic partial differential equations (PDEs). This results in a boundary control problem, where the control objectives are to reduce the amount of NO_x emissions and ammonia slip to the fullest extent possible using the inlet concentration of ammonia as the manipulated variable and assuming that the concentrations of nitric oxide and nitrogen dioxide and ammonia, are measured at the SCR inlet and outlet. The proposed method combines the method of characteristics, spectral decomposition and the model predictive control (MPC) approach. For performance comparison purposes, the open-loop dynamic optimization problem is solved via Direct transcription (DT) to compute the upper performance limit for the optimal SCR problem. The results show that the proposed approach is able to achieve a very high level of control performance in terms of NO_x and ammonia slip reduction.

1. Introduction

Heavy-duty diesel engines are important in transportation and power generation applications, power systems for vehicles and industrial equipments [1,2]. Key disadvantages of diesel engines include the emission of significant levels of particulate matter and oxides of nitrogen (NO_x), which are known to have detrimental health and environmental effects [2]. As a result, manufacturers have developed emission control technologies in an effort to meet or exceed mandated requirements. The main components of the diesel engine emission system include the diesel oxidation catalyst (DOC), which is oxidises carbon monoxide and hydrocarbons, a particulate filter (DPF) to capture soot and selective catalytic reduction (SCR) [2]. Within the SCR section of the emission control system, NO_x is catalytically reduced to nitrogen and water using ammonia. A particular care must be taken in the operation of the emission control system to ensure that the ammonia dosing is accurate; otherwise, the excess ammonia, which is given the term “ammonia slip”, is emitted. Emission of ammonia is an additional environmental hazard in the operation of diesel engines.

In diesel-powered engines, the optimal dosage of ammonia in SCR is a challenging problem because the operating conditions of SCR during a drive cycle changes. Although the overall dynamics of the system are fast, the interplay of fast dynamics reflected in catalytic conversion processes is entangled with the transport-processes of stored NH_3 which may act as buffer due to its storage capacity and impact the fast and slow time scale of the overall system's dynamics. Furthermore, the dynamics of this system are fast, so it is crucial to develop a high-performance control technique that quickly calculate the needed control actions for such a fast system. Developing reliable dynamic models and control techniques for the optimal operation of SCR has attracted attention of researchers in academia and industry. To balance high NO_x reduction efficiency and low ammonia slip, several urea dosing control approaches have been recently proposed [3,4]. Chen and Tan proposed a 3D dynamic model based on the Navier–Stokes equations for the SCR [5]. They estimated the kinetic parameters of the model using

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experimental data and an optimization technique that integrates the Taguchi method, a genetic algorithm, and a neural network based auxiliary model. Their results indicate that the optimized SCR can achieve NO_x reduction rate up to 99.93%. In addition, the optimal operating temperature is considerably low and the ammonia slip is insignificant. They demonstrated that the proposed design provides much better energy savings and is environment-friendly in comparison with the conventional designs [5]. Map-based urea dosage strategies are currently used in vehicles [6]. To improve catalyst temperature prediction and the engine-out NO_x prediction [7], simple models, which can be considered as the preliminary models of the SCR catalyst dynamics, are used. The need for high NO_x reduction and the introduction of Zeolite catalysts has persuaded researchers to focus on the NH_3 coverage control [6]. A reduced order model, obtained on the basis of the first principles for NH_3 coverage, can improve NH_3 slip control. Due to safety margins and robustness issues, feedback SCR control has attracted considerable attention. Most of the feedback strategies use a PI controller, a coverage observer, and a state feedback controller. Other control approaches are found, such as model reference adaptive control [3], sliding mode control [8], backstepping based nonlinear ammonia coverage ratio control [4], a computationally-efficient model predictive control assisted method [9] and LPV (linear parameter-varying) gain-scheduled control using robust control techniques and LMIs [10]. All techniques developed to date use models comprised of ODEs to control the SCR and use inlet and outlet sensors for the state and parameter estimation. Measured chemical species in diesel-engine realizations are usually NO_x (NO and NO_2), while the NH_3 concentration can be inferred from the accurate enough measurements of outstream components. The main drawback of these techniques is that models developed based on ODE cannot capture important SCR dynamics, so the highest performance of the SCR cannot be achieved; however, good performance can be achieved by using models involving a large number of ODEs at the expense of computational time. Using distributed parameter control techniques, one can obtain high level of performance, as the main dynamics of system are captured. Therefore, high performance control design should employ the full complex SCR model rather than an approximation. There exist various control techniques that have been developed to control hyperbolic or parabolic PDEs, but no techniques for systems that include coupled hyperbolic and parabolic PDEs exist in the literature to the best of our knowledge. Researchers have developed various control techniques for distributed parameter systems, such as optimal control [11,12] and backstepping [13,14]. A control design technique is proposed in this work for systems modelled by coupled hyperbolic and parabolic PDEs. The proposed control technique uses a new technique that combines the method of characteristics and spectral decomposition to solve complex systems like the SCR, and is named characteristics-based nonlinear model predictive control (CBNMPC). The method of characteristics uses exact transformation to change hyperbolic PDEs into set of ODEs, that can be solved along the characteristics curves [15,16]. On the other hand, spectral decomposition is used to convert parabolic PDEs into a finite set of ODEs that capture important dynamics of parabolic PDEs [17]. Characteristics-based model predictive control (CBMPC) was first developed by Shang [18] for systems with linear and quasilinear hyperbolic PDEs. In this work, the CBNMPC idea was adapted for control of systems with coupled hyperbolic and parabolic PDEs. CBNMPC uses nonlinear optimization techniques and continuous models rather than using convex optimization techniques for discrete linear or linearized models, as does CBMPC developed by Shang [18]. DPNMPC belongs to the family of optimal control techniques used to determine optimal control actions for nonlinear systems. In addition, NMPC can find the global optimal control actions in systems consisting of convex models. Note that it is assumed that measurements of the state are available, however, in practice, it is not possible to have measurements along a tube, so an observer is needed to estimate the states along a tube. This could be the subject of future research.

The paper is organized as follows. Section 2 describes the chemical process and its distributed parameter model. An equivalent lumped parameter model has been developed in Section 3. In order to do so, a combination of the method of characteristics and spectral factorization is used. Section 4 focuses on the design of a CBNMP algorithm for the lumped parameter SCR model that has been developed in an earlier portion of the paper. Also, an open-loop control approach is developed using direct transcription (DT). This is used to determine the best achievable control performance, assuming that future operating conditions and disturbances of plant are known. Finally, numerical simulations have been performed to show the performances of the developed approach.

2. Process description and modelling

Two different types of SCR exist. The first type uses ammonia or urea solution to reduce nitrogen monoxide (NO) and nitrogen dioxide (NO_2) to nitrogen and water. Urea is favored because it can be handled more easily. The second type uses hydrocarbons to reduce the NO_x emissions. It is convenient to use diesel fuel as the source for the hydrocarbons, but a SCR can use other hydrocarbons. The ammonia-based SCR can reduce up to 95% of NO_x emissions; whereas, NO_x reduction by the hydrocarbon injection is limited to approximately 40%. Also, hydrocarbon-based SCR is sensitive to temperature [19]. Note that the type of SCR technology used here is cummins heavy-duty urea-SCR.

Factors that influence the performance of SCR include the distribution of ammonia in the gas stream upstream of monolith and gas velocity profile through the catalyst. In addition, the angle of ammonia injection plays an important role in effectively reducing NO_x emissions because it affects the proper distribution of ammonia. Another facet of operation of SCR is the proper determination of ammonia flow for each operating condition. The ammonia flow is in general controlled based on NO_x measurements taken from the gas stream or existing performance curves from an engine manufacturer. The ammonia slip is an industry term for unreacted ammonia exiting the SCR. This occurs when more ammonia is injected into the gas stream than the amount needed for the NO_x reduction. Temperature is one of the important factors limiting SCR performance. Diesel engines all have a period of start-up during which exhaust temperatures are too low for the ammonia to react with NO_x emissions; as a result, there are NO_x emissions or a large ammonia slip in the tailpipe [19,20].

Urea solutions are used as a source of ammonia in SCR, but in exhaust aftertreatments that include both DOC and SCR, because of limitations on the residence time between DOC and SCR catalyst and the higher dynamics of system, the complete conversion of urea could not be achieved and improvements in achieving chemical conversion to environmentally acceptable products is of high interest. Hence, a passenger cars use urea solutions as the external source of ammonia. The SCR catalysts used in vehicles are typically an extruded monolith with 300 cells per square inch (cpsi), a wall thickness of 0.32 mm with various total volumes range from 8 to 45 l.

There are several operating modes in a drive cycle. In other words, the engine speed and load changes during a drive cycle because a driver accelerates, decelerates or stop the vehicle; as a result, the outlet temperature and concentration of the components of diesel emission change. Thus, the inlet condition of SCR constantly changes, so there is no steady state operation in SCR. The control of SCR is therefore a challenging issue. A typical process diagram of SCR is shown in Fig. 1.