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# Nonlinear Adaptive Control of Exhaust Gas Recirculation for Large Diesel Engines

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**Abstract:** A nonlinear adaptive controller is proposed for the exhaust gas recirculation system on large two-stroke diesel engines. The control design is based on a control oriented model of the nonlinear dynamics at hand that incorporates fuel flow and turbocharger speed changes as known disturbances to the exhaust gas recirculation. The paper provides proof of exponential stability for closed loop control of the model given. Difficulties in the system include that certain disturbance levels will make a desired setpoint in $O_2$ unreachable, for reasons of the physics of the system, and it is proven that the proposed control will make the system converge exponentially to the best achievable state. Simulation examples confirm convergence and good disturbance rejection over relevant operational ranges of the engine.



*Keywords:* Exhaust gas recirculation, diesel engines, nonlinear control, adaptive control, modelling for control, parameter estimation.

## 1. INTRODUCTION

Emissions from diesel engines are subject to restriction due to awareness of environmental effects of the emissions. The Tier III restrictions, limiting the emission of $NO_x$ from marine diesels in selected areas, as was presented by the International Maritime Organization, IMO (2013) will be introduced in 2016. The IMO Tier III rules for environmental protection specifies a reduction of 76% of $NO_x$ emission compared to the Tier II standard in specified Emission Control Areas, including most of the North American coastal areas, among others. This motivates the ship industry to develop technologies that reduce the emissions of $NO_x$.

One of such technologies is Exhaust Gas Recirculation (EGR), which has been applied to four-stroke engines in the automotive industry for several decades. The principle is to recirculate part of the exhaust gas into the engine intake. This decreases the oxygen content and increases the heat capacity of the scavenging gas. In turn the peak temperatures during combustion are decreased, resulting in a decrease in the formation of $NO_x$ during combustion. Unfortunately, lowering the oxygen content of the scavenging gas also affects the combustion efficiency. At excessively low scavenge air oxygen levels, the engine will produce visible smoke. Thus the optimal scavenging oxygen level is a compromise between fuel economy, smoke formation and $NO_x$ emissions.

To prepare for the Tier III restrictions, engine designer MAN Diesel & Turbo (MDT) has introduced EGR technology on their large two-stroke marine diesel engines. Other technologies for $NO_x$ reduction are also being used, but the scope of this paper is the control of the EGR system. As the scavenge pressure of a two-stroke engine is higher than the exhaust pressure, a blower is used in the EGR string to provide a pressure increase. The blower speed must be carefully controlled to obtain an EGR flow that leads to the appropriate amount of oxygen in the scavenging gas. A simplified schematic of the engine air path is shown in Figure 1. Some components that are not essential to the paper have been omitted from the Figure. The EGR unit shown in the Figure removes corrosive $SO_x$ and cools the recirculated gas.

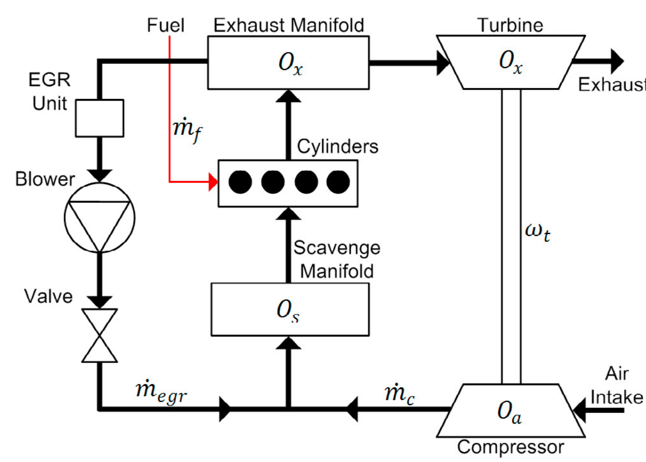


Fig. 1. Simplified overview of engine gas flows.

The overall control objective is to obtain feedback control of the oxygen concentration $O_s$ in the scavenge manifold using either the speed setpoint of the EGR blower or

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the opening of the EGR valve as actuator input. This method has been applied to several engine setups. During stationary running conditions existing fixed gain control has shown ability to keep $O_s$ adequately close to a setpoint. However, this feedback control, being based on an $O_s$ measurement with inherent sensor dynamics and measurement delay, is an essential limitation for performance. This becomes an issue when handling hard acceleration of the ship and in high sea conditions where waves have significant impact as a fluctuating load torque on the propeller shaft (Hansen et al., 2013a). In both these conditions the engine RPM controller adjusts the flow of fuel into the cylinders and thus changes the appropriate EGR flow. The slow nature of the system and difficulties inherent to measuring oxygen concentration in the scavenge manifold makes the control system react slowly to such disturbances. To avoid smoke formation from too low oxygen, it is currently necessary to limit the possible ship acceleration when the EGR system is running. Such a limitation is undesirable and far from possible in all operating situations. Therefore, an alternative control concept is needed that can cope with pressure dependent sensor measurement delay, sensor dynamics and the nonlinear dynamics of the gas recirculation system, and yet provide a high performance closed loop control.

A clear difference between the EGR control system developed by MDT and the EGR systems in the automotive industry is the effort available for commissioning an EGR controller for an engine configuration. Each automotive engine design is thoroughly tested on a test bench before releasing for large scale production. In opposition to this the specific large two-stroke engine designs are produced in very low numbers, they are sometimes not tested until the first engine is produced and even then very limited test time is available due to very high test running cost. It is furthermore possible that a large two-stroke engine will be reconfigured during its time of operation. The consequences of these practical issues are that manual tuning for the individual design is not applicable and that observer design based on a priori data is impractical. This means that the control design must be robust not only towards changes in system behaviour but also towards imprecise design data.

Numerous examples of modelling and control of EGR systems for automotive engines exist in literature. Notable examples are Wahlström and Eriksson (2011a), Wahlström and Eriksson (2011b) and van Nieuwstadt et al. (2000). Jankovic et al. (2000) proposed nonlinear control of automotive EGR systems using a control Lyapunov function. Modelling of large two-stroke engines have been treated in both classical literature, e.g. Blanke and Andersen (1984), Hendricks (1986) and more recently in Theotokatos (2010) and Hansen et al. (2013b) though only the latter includes an EGR system. Hansen et al. (2013a) presented EGR control design with SISO methods and feed forward of the fuel index. The main issues were found to be parameter sensitivity and the dead time of the oxygen sensor.

This paper introduces an adaptive nonlinear controller for the EGR system, based on a system model that is significantly simpler than traditional mean value models. The control law incorporates known disturbances for faster rejection of these. Exponential stability of the simplified closed loop system is proven by Lyapunov's direct method. Simulation examples confirm convergence and disturbance rejection properties of the controller.

The control oriented model of the EGR system behavior is briefly introduced in Section 2. Control design and stability proofs are found in Section 3. The closed loop system of the simple EGR model and the controller is simulated in Section 5 followed by a discussion of the validity of the results in Section 6.

## 2. SYSTEM MODEL

This section introduces a model of the scavenge oxygen dynamics in the EGR system. The model is intended as a simplification that is useful for controller design as opposed to conventional mean value approaches that represent a more sophisticated replication of physical processes. In the simple model, the nonlinearities of the stationary system response is used as an input nonlinearity to a first order system. The end result is a first order Hammerstein system with multiple inputs and one output.

### 2.1 Static model

The static model of the scavenge manifold oxygen fraction assumes that the ambient oxygen fraction $O_a$, compressor mass flow $\dot{m}_c$, recirculated mass flow $\dot{m}_{egr}$ and fuel mass flow $\dot{m}_f$ are known.

During stationary conditions, the oxygen fraction in the exhaust $O_x$ is a function of compressor flow, ambient oxygen fraction, fuel flow $\dot{m}_f$ and stoichiometric oxygen-to-fuel ratio $k_f$. Assuming a complete, lean combustion, $O_x$ is modelled as in Hansen et al. (2013b).

$$O_x = \frac{\dot{m}_c O_a - \dot{m}_f k_f}{\dot{m}_c + m_f} \quad (1)$$

The oxygen fraction in the scavenge manifold $O_s$ at stationary state is the average of ambient and exhaust oxygen weighted by compressor flow and recirculated flow $\dot{m}_{egr}$, respectively.

$$O_s = \frac{\dot{m}_c O_a + \dot{m}_{egr} O_x}{\dot{m}_c + \dot{m}_{egr}} \quad (2)$$

Combining (1) and (2) leads to a static model of $O_s$, based on the 3 major flows.

$$O_s = O_a - (O_a + k_f)\frac{\dot{m}_f}{\dot{m}_c + \dot{m}_f} \cdot \frac{\dot{m}_{egr}}{\dot{m}_c + \dot{m}_{egr}} \quad (3)$$

Isolating the recirculated flow in (3) leads to an expression that is useful for the control design.

$$\dot{m}_{egr} = \frac{\dot{m}_c(O_a - O_s)}{O_s - \frac{\dot{m}_c O_a - \dot{m}_f k_f}{\dot{m}_c + \dot{m}_f}} = \frac{\dot{m}_c(O_a - O_s)}{O_s - O_x} \quad (4)$$

The recirculated flow and the fuel flow are both assumed to be available to the controller, but the compressor flow is not. Estimation from a compressor map is ruled out as maps that covers all operating points are not practically available for each engine. Instead the flow is approximated as a simple function of compressor speed $\omega_t$

$$\dot{m}_c = \omega_t^a \cdot \theta \quad , \quad a \in [1:2] \quad , \quad \theta > 0 \quad (5)$$

where $a$ and $\theta$ are constants. A similar approximation was done by Hendricks (1986) where the compressor flow