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Real-time control of a two-stage serial VGT Diesel engine using MPC

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Abstract: Real-time model predictive control (MPC) is used to experimentally assess the transient air-path performance of a two-stage serial variable geometry turbocharger (VGT) fitted to a light duty Diesel engine. The control model is based on a mean value engine model (MVEM) that is developed using data from the engine with a single stage turbocharger and modified to simulate the two-stage arrangement. A tip-in transient manoeuvre is used to assess system performance, in particular the boost-control where MPC is used to achieve close to optimal performance. This paper explores the improvement in transient performance when using two VGT turbochargers in series and considers where the differences between experiment and simulation occur.
In general it is shown that there is good agreement between the experimental and simulated system performance. It is observed that the VGT actuator position must be well matched to the modelled position to achieve good on-engine performance. Other factors which affect the experimental performance are related to the actuator dynamics, cyclic-behaviour of the real-time pressure states, time-constants effecting the temperature measurement and the difficulty in accurately modelling the heat transfer in the exhaust, turbines and housings.

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1. INTRODUCTION

Engine downsizing is a key enabler for reducing fuel consumption and lowering emissions. This creates a requirement for a high level of pressure charging to achieve the required engine power. One disadvantage that highly downsized engines can suffer from is a slow build-up of torque during transients, often referred to as turbo-lag. For gasoline engines the air-fuel ratio is in general controlled to stoichiometric proportions and for Diesel engines these generally run lean in order to avoid excessive particulate emissions. Accordingly, the maximum engine out torque is necessarily limited by the mass of oxygen delivered to the the cylinders. At low engine speed and loads the turbine(s) are ineffective in producing usable work for the compressor(s) and therefore the inlet air-charge density is low. To generate significant boost the turbocharger much first be accelerated and thus the rate of acceleration has a significant effect on the driveability and opportunity to further downsize the engine. To minimize turbo-lag a range of advanced hardware solutions can be considered. Depending on the application these can include: multi-stage systems, electric compressors, electrically assisted turbochargers, variable geometry turbines (VGT) and supercharger/turbocharger combinations (Martinez-Botas et al. (2011)).

When selecting the appropriate hardware for a particular application transient response is an important consideration. Tools which can provide a representative assessment of the transient performance can be used to assist in the selection process. This leads to a requirement for a sufficiently accurate modelling environment and appropriate control scheme. Mean value engine models (MVEM) have been used extensively in the literature for air-path studies and generally regarded to be of sufficient fidelity. Model predictive control (MPC) is proposed as the control scheme to coordinate the actuators, observe system constraints and be readily transferable to alternative air-path architectures without excessive amounts of tuning - notwithstanding the initial modelling effort. Furthermore, MPC has been demonstrated to give close-to-optimal performance for airpath applications (Cieslar et al. (2014)) with only modest and intuative tuning of the controller weights, whereas other ad-hoc multivariable controller tuning can result in under-performance of the closed-loop system.

MPC has been demonstrated to be a useful tool for a range of automotive and engine studies (del Re et al. (2010)) due to the benefits of meeting constraints and good coordination of multi-input multi-output systems. Real-time MPC control of the engine airpath has been achieved with both implicit and explicit solutions. Behrendt et al. (2011) demonstrated that implicit solutions can be feasible for new generation engine control units, for problems with low numbers of actuators and relatively short control horizons. Explicit MPC is another approach to for real-time control of airpath systems without the computational

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burden associated with online optimization (Zhao et al. (2013); Stewart and Borrelli (2008); Hadef et al. (2013)).

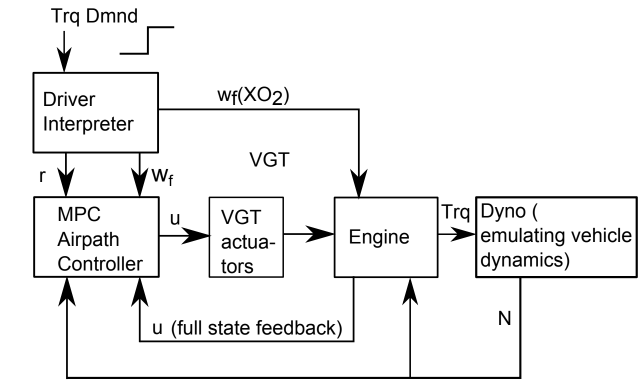

Fig. 1. Engine Control Structure

The authors simulated several two-stage turbocharger configurations to evaluate their potential performance gains over the standard single stage VGT. From a transient performance perspective, the use of two actively controlled VGT turbochargers offered significant improvements over the more conventional configurations, in which at least one stage usually has a fixed geometry turbine (with bypass). In this paper we compare the simulated predicted behaviour of a two-stage series VGT to the experimental performance. For the simulation study a MVEM model is controlled using linear MPC and the same controller then applied to the physical system. A schematic of the control structure is given in figure 1. The transient under consideration is a 3rd gear step change to full torque, with the aim of accelerating a vehicle as quickly as possible. This demand is interpreted as a step change in fuel flow rate, w_f, subject to the smoke limit which is a function of the intake oxygen mass concentration, XO_2. The demand also corresponds to a change in the boost reference, r, with the aim of increasing the intake manifold pressure as quickly as possible, thereby minimising the duration that the system is smoke limited. The air-path controller has full state feedback with fuel flow rate, engine speed and ambient conditions as measured model disturbances.

The paper is organized as follows. The experimental setup is described in section 2, the modelling approach given section 3. The MPC control approach is described in 4 followed by the results and finally some conclusions.

2. TWO-STAGE VGT EXPERIMENTAL SETUP

The engine under consideration is a 2.0l, four cylinder Diesel engine designed to meet Euro V emissions regulations. Data to parametrize the MVEM was taken from the engine with the standard OEM single stage VGT hardware. The air-path hardware was subsequently changed to a two-stage serial VGT system for transient analysis, arranged as in figure 2. This system was fabricated with off-the-shelf single-stage units and as such the pipe work to, from and between the units was bespoke. The two units were arranged so that a full flow capacity low pressure compressor would supply air to to a smaller high pressure compressor. An electronic throttle valve was fitted to allow the flow to bypass this high pressure compressor. On the exhaust side the high pressure VG turbine was closely coupled to the exhaust manifold. The LP compressor and turbine had wheel diameters of 44 and 40 mm respectively, the HP were sized 40 and 37 mm respectively. The combined compressor and turbine inertia of the HP stage was approximately two-thirds of the LP stage.

An exhaust valve was also fitted to the exhaust manifold and the total flow of this and the HP turbine directed to the LP VG turbine which was sized to swallow the engine exhaust flow. Bends in the pipework and changes in diameters between devices were chosen with consideration for the flow path but the system was not optimized. In general the exhaust valve is used for medium to high exhaust flow conditions to prevent the VGT choking.

ATI Vision and No-hooks was used with a development powertrain control module (PCM) which allowed the air-path control to be performed remotely without affecting the fuelling control. The real-time air-path control was achieved using a dSPACE modular expansion box system with a DS1006 processor card. Selected signals from the PCM were sampled from the CAN BUS to be available in dSPACE. Exhaust gas recirculation was disabled for the purposes of this study.

In addition to the engine variables available from the PCM the engine was instrumented with pressure sensors and fast response 0.5 mm thermocouples in the key volumes. Each compressor was fitted with a speed sensor. The engine model was based on 7 control volumes: pre-LP compressor, post-LP compressor, post-HP compressor, inlet manifold, exhaust manifold, post-HP turbine and post LP turbine. Fig. 2 shows the general engine layout and location of key instrumentation. For this study the compressor bypass is not required as this is only opened for high flow and high engine speed operation.

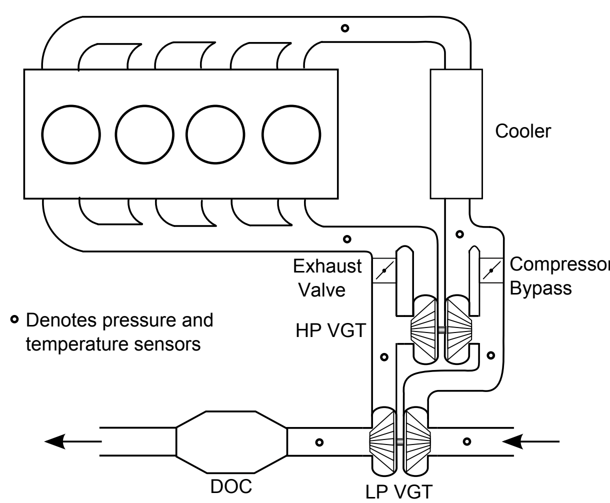

Fig. 2. Engine layout with sequential two-stage VGT turbocharger arrangement

The turbine vane positions were controlled using a pneumatic actuator with position feedback. The VGT arm is connected to a diaphragm and the position is determined by a balance of pressure inside the reservoir, opposing spring force and load on the arm caused by aerodynamic forces on the blades inside the turbine. The emptying and filling dynamics and the force balance is nonlinear, and in addition the system suffers from stiction. A full

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