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Model and discretization impact on oscillatory optimal control for a diesel-electric powertrain

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Abstract: A mean value engine model is used to study optimal control of a diesel-electric powertrain. The resulting optimal controls are shown to be highly oscillating for certain operating points, raising the question whether this is an artifact of discretization, modeling choices or a phenomenon available in real engines. Several model extensions are investigated and their corresponding optimal control trajectories are studied. It is shown that the oscillating controls cannot be explained by the implemented extensions to the previously published model, nor by the discretization, showing that for certain operating points the optimal solution is periodic.

1. INTRODUCTION

The engine speed of a conventional vehicle is normally decided by the wheel speed and the gear ratio. In a diesel-electric powertrain this mechanical path between the combustion engine and the wheels is replaced by an electric path instead. This introduces an extra degree of freedom since the engine speed can be controlled independently of the wheel speed, which offers the potential of both optimizing the performance and consumption since the operating point of the diesel engine can be controlled more freely than in a conventional powertrain. This of course raises the question of how to use this extra degree of freedom.

Previously it has been studied how to optimally control the powertrain between two different power levels, see Sivertsson and Eriksson [2015a,b]. For off-highway machinery the driving patterns are normally very transient, something that is captured in the World Harmonized Transient Cycle (WHTC), see WHDC Working Group [2005], shown in Fig. 1. The WHTC can be divided into 11 traction phases, defined as the period between two idle periods, where idle is assumed to occur when the engine speed is the idle speed and no power is required. Here the phases where the engine is motored, i.e. $P_{gen} < 0$ are ignored and P_{gen} is in those cases set to zero.

To investigate the potential of the diesel-electric powertrain and how to best exploit the extra degree of freedom introduced by the electrification of the powertrain, minimizing fuel for the WHTC is cast as an optimal control problem (OCP). In a conventional powertrain WHTC prescribes both engine speed and output power, but here engine speed is a degree of freedom and also optimized. If this OCP is solved for phase 8 in the WHTC the resulting controls are very oscillatory, see Fig. 2, $t \in [670, 678], [684, 687]$. It is mentioned in Sivertsson and Eriksson [2015a] that the optimal solutions in transient optimal control of a diesel-electric powertrain are often oscillatory and in Asprion et al. [2014] the unconfirmed

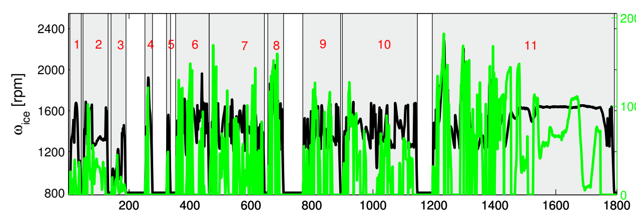

Fig. 1. The WHTC and its traction phases.

hypothesis is that the oscillations seen in the optimal variable geometry turbine (VGT) control of a diesel engine are due to decrease in the gas exchange losses. This is due to that the exhaust manifold pressure oscillates with the VGT position whereas the intake manifold pressure remains unaffected due to the slower turbocharger dynamics. This could indicate that the optimal solution is in fact periodical as described in Gilbert [1976], Gilbert [1977]. Other possible explanations are either that the solution is along a singular arc and that the controls are therefore oscillatory, as discussed in Schwartz [1996], or that it is an integration error exploited by the algorithm to decrease the criteria as shown in Hellström et al. [2010]. In both these cases it would be suspected that the frequency of the oscillations depend on the discretization. To test this hypothesis a single operating point is selected and studied using a very fine time discretization.

2. CONTRIBUTIONS

The contributions of this paper is a deeper study of the occurence of oscillating controls for diesel-electric powertrains as a solution for optimal control problems. More specifically it studies whether the observed oscillations are an artifact of the discretization. It also investigates if the oscillations can be explained by the models used and whether or not extending the model impacts the oscillating solutions. The paper also presents a fast and accurate residual gas model suitable for use in an optimal control context.

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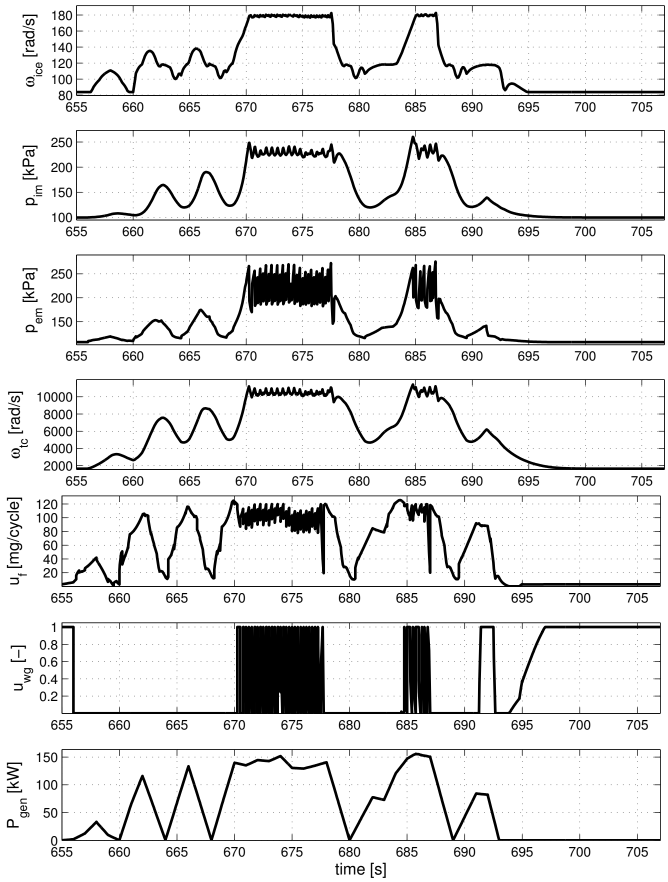

Fig. 2. The optimal solution to phase 8 of the WHTC, with ω_{ice} as a degree of freedom. The resulting controls are highly oscillatory, see $t \in [670, 678], [684, 687]$

Table 1. Symbols used

Symbol	Description	Unit
p	Pressure	Pa
T	Temperature	K
ω	Rotational speed	rad/s
$\dot{m}$	Massflow	kg/s
P	Power	W
M	Torque	Nm
E	Energy	J
Π	Pressure ratio	-
V	Volume	m^3
γ	Specific heat capacity ratio	-
c_p	Specific heat capacity constant pressure	$J/(kg \cdot K)$
c_v	Specific heat capacity constant volume	$J/(kg \cdot K)$
R	Gas Constant	$J/(kg \cdot K)$
u_f, u_{wg}, P_{gen}	Control signals	mg/cycle, -, W
J	Inertia	$kg \cdot m^2$
BSR	Blade speed ratio	-
ϕ	Fuel-air equivalence ratio	-
λ_{min}	Air-fuel smoke-limit	-
x_r	Residual gas fraction	-
MFR	Fuel to mass ratio	-
q_{HV}	Lower heating value	J/kg
r_c	Compression ratio	-

3. MODEL

The basic model used can be downloaded in the **LiU-D-El**-package from systems software [2014] and is described in detail as $MVEM_o$ in Sivertsson and Eriksson [2014]. The modeled diesel-electric powertrain consists of a 6-cylinder diesel engine with a fixed-geometry turbine and a wastegate for boost control, with a generator mounted on the output shaft. The states of the MVEM are engine and turbocharger speeds, $\omega_{ice/tc}$, and inlet and exhaust manifold pressures, $p_{im/im}$. The controls are injected fuel mass, u_f, wastegate position, u_{wg}, and generator power, P_{gen}. The engine model consists of two control volumes, intake and exhaust manifold, and four restrictions, compressor, engine, turbine, and wastegate. The governing differential equations of the MVEM are:

Table 2. Subscripts used

Index	Description	Index	Description
ice	Engine	$GenSet$	Engine-Generator
im	Intake manifold	em	Exhaust manifold
c	Compressor	ac	After compressor
t	Turbine	wg	Wastegate
f	Fuel	tc	Turbocharger
a	Air	e	Exhaust
gen	Generator-electrical	$mech$	Generator-mechanical
ref	Reference	$c, surge$	Compressor surge-limit
vol	Volumetric	d	Displaced
$fric$	Friction	$pump$	Pumping
ig	Indicated gross	eo	Engine out
amb	Ambient		

$$\frac{d\omega_{ice}}{dt} = \frac{P_{ice} - P_{mech}}{\omega_{ice} J_{GenSet}} \tag{1}$$

$$\frac{dp_{im}}{dt} = \frac{R_a T_{im}}{V_{im}} \left(\dot{m}_c - \dot{m}_{ac}\right) \tag{2}$$

$$\frac{dp_{em}}{dt} = \frac{R_e T_{em}}{V_{em}} \left(\dot{m}_{ac} + \dot{m}_f - \dot{m}_t - \dot{m}_{wg}\right) \tag{3}$$

$$\frac{d\omega_{tc}}{dt} = \frac{P_t \eta_{tm} - P_c}{\omega_{tc} J_{tc}} \tag{4}$$

For a complete list of the symbols used in the paper, see Table 1-2.

4. PROBLEM FORMULATION

This paper uses the MVEM to study optimal stationary operation, or lack of it in the case of oscillating controls.

4.1 Stationary optimization

As a reference for the dynamic optimization, three stationary optimization problems are first solved, to find the following three stationary points for the given ω_{ref}, P_{ref}-combination: The maximum efficiency, ϕ_{max}, the maximum fuel/air-ratio, η_{max}, and the minimum fuel/air-ratio, ϕ_{min}. $\eta = \frac{P_{gen}}{\dot{m}_f q_{HV}}$ is the efficiency of the powertrain and ϕ is the fuel/air-ratio. These problems are solved to find the optimal operating point for stationary operation and also the limits for stationary operation.

4.2 Dynamic optimization

The main optimal control problem studied is:

$$\begin{aligned} \min_{u(t)} \quad & \int_0^T \dot{m}_f \\ \text{s.t.} \quad & \dot{x}(t) = f(x(t), u(t)) \\ & (x(t), u(t)) \in \Omega(t) \end{aligned} \tag{5}$$

where x is the state vector of the MVEM, $\dot{x}$ is the state equations (1)-(4), and $u = [u_f, u_{wg}, P_{gen}]$. The optimal control problems are also subject to a set of constraints, namely: