

Optimizing the Transient of an SI-Engine Equipped with Variable Cam Timing and Variable Turbine

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ABSTRACT

As the engines of today decrease in displacement with unchanged power output, focus of today's research is on transient response. The trend of today is to use a turbocharger with high boost level. For SI-engines a regular WG-turbocharger has been used, but in the future, when the boost level increases together with higher demand on the transient response, a Variable Nozzle Turbine (VNT) will be used together with Variable Valve Timing (VVT). As the degree of freedom increases, the control strategies during a transient load step will be more difficult to develop.

A 1D simulation experiment has been conducted in GT-Power where the transient simulation was "frozen" at certain time steps. The data from these time steps was put in a stationary simulation and the excessive energy was then bled off to obtain the same conditions for the engine in the stationary simulation as if the engine were in the middle of the transient. This method allows a faster and easier way to obtain a good control strategy for the VNT turbine and the VVT during a transient load step.

The method can be used to find VNT/VVT settings strategies for the transient control with a good and robust result.

INTRODUCTION

The Spark Ignited (SI) engines of today have a quite large displacement with a moderate or no boost level. A large engine leads to high friction losses and pumping losses. Legislation and people's consciousness lead to a decrease of engine fuel consumption, and the trend of today is to decrease

the engine size to decrease the losses. The boost level is often increased to maintain the same power and torque level.

The idea of having a small engine with high boost pressure which allows a high power output is rather old. During the early 80's the Formula 1 cars had as much as 1500 hp out of 1.5l. The problem is not to obtain power, but not to lose the drivability of today's engine. As the specific power output is increasing, a lot of instruments are available to maintain a good drivability of the engine. Modern SI engines usually have high-pressure direct fuel injection, variable camshafts and some sort of turbo.

The problem is not that the engineer lacks tools to maintain a good engine behavior, but for the engineer to know how to use all tools in a good and fast/cheap way to obtain this good engine behavior.

This paper introduces a 1D simulation method to quickly find control strategies that leads to a good engine behavior during a transient load step when using a variable nozzle turbine (VNT) and variable valve timing (VVT).

EXPERIMENTAL SETUP

This study has been conducted in GT-Power [1]. The focus has been on transient response and to find a fast way to determine a good strategy for the VNT together with VVT during a transient.

The reference engine that all measurements were conducted on was a 2 liter SI engine with direct injection, VVT and VNT. The base engine is from the GM L850/Ecotec family. The original turbocharger was replaced with a Mitsubishi

VNT turbocharger (MHI TD04HL-VG Turbine and a TD04H-15TK31 compressor).

All research has been made at a speed of 1750 rpm and all transients starts at an Indicated Mean Effective Pressure (IMEP720) of 3 bar. The goal was to achieve as high IMEP720 as possible after 1.5 s (according to GM practice) with a goal of 20 bar IMEP720. The drivability of the engine should not be affected of the different strategies during the transient and the BSFC should be as low as possible when running the engine at 3 bar IMEP720.

The engine Control Unit is a rapid prototyping system which enables controlling the VNT/VVT independently. For this work the VVT was decided to have a central positioned overlap (to reduce the degrees of freedom of the task). Both the intake and the exhaust cam are moved equal on both side of top dead center (TDC). For simplicity, the overlap (OL) is described as a function of the exhaust valve maximum opening position (EMOP), see [equation 6](#). EMOP can be varied between 248 (EMOPmin) and 288 crank angle degrees (CAD) which gives an overlap of (0-78 CAD OL).

$$OL = EVC - IVO \quad (1)$$

$$EVC = EMOP + 111 \quad (2)$$

$$IVO = IMOP - 115 \quad (3)$$

EVC and IVO stands for Exhaust Valve Closing and Intake Valve Opening. IMOP stands for Intake valve Maximum Opening Position. The overlap can be defined as below

$$OL = EVC - IVO = EMOP - IMOP + 226 \quad (4)$$

Since IMOPmin and EMOPmin are known parameters, IMOP can be written as a function of EMOP according to [equation 5](#).

$$IMOP = IMOP_{\min} - (EMOP - EMOP_{\min}) \quad (5)$$

$$IMOP_{\min} = 436$$

$$EMOP_{\min} = 248$$

The function for overlap (OL) is

$$OL = EMOP - (IMOP_{\min} - (EMOP - EMOP_{\min})) + 226 \quad (6)$$

The equations above are only an explanation of how the VVT is controlled in the ECU and in the GT-power simulations.

The GT-power model was calibrated with engine measurements at different speeds (1500, 1750, 2000 and 3000 rpm) and loads (3, 7, 14, 20 bar and WOT IMEP720). The anchor angle (CA50) and the burning duration (BDUR) for the Wiebe function were mapped as a function of load (IMEP720) and residuals (EMOP) to get a good correlation for the combustion, especially during a transient load step. [Figure 1](#) shows the measured and simulated cylinder pressure using the mapped Wiebe parameters.

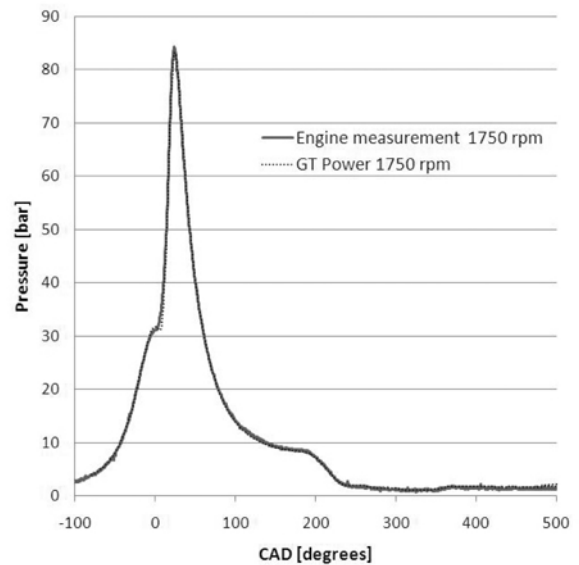


Figure 1. Cylinder pressure measured in engine dyno compared to simulated cylinder pressure at 1750 rpm WOT.

For transient simulations, the simulation is run in steady state for 2 s to stabilize. After 2 s the throttle is opened and the VNT/VVT are set.

To be sure that the Wiebe function considers the residuals effect on the combustion during a transient load step, 12 different load steps with different VNT/VVT settings were simulated and correlated to engine measurements. The results for the CA50, BDUR and the turbine speed during a transient load step are shown in [Figure 2,3,4](#).

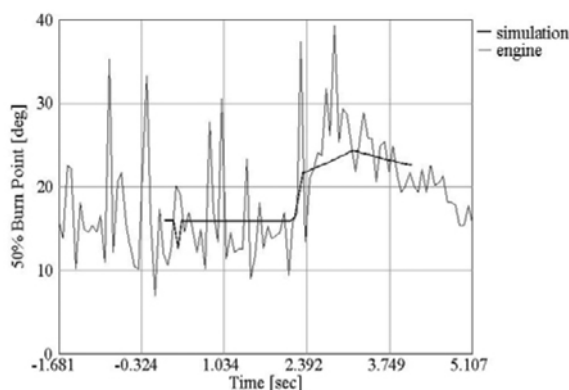


Figure 2. The CA50 for simulation and engine measurement during a load step at 1750 rpm.

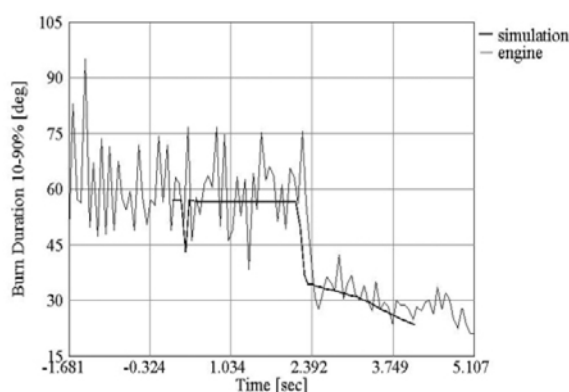


Figure 3. The burning duration for a simulation and engine measurement during a load step at 1750 rpm./

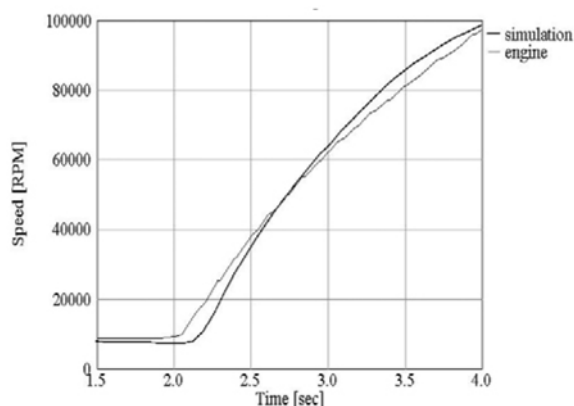


Figure 4. The turbine speed during a transient load step for the simulation and engine measurement.

METHOD

When using a VNT turbine together with VVT, the degrees of freedom are increasing rapidly. A strategy is needed to control both the VNT and the VVT during a transient. This strategy varies from case to case. A way to find this strategy

is to use the trial and error method for each case. However the trial and error as optimization method is too time-consuming considering the degrees of freedom. A new method is proposed in this paper, which in the end is a much easier and faster way to find a good transient control strategy.

During a transient, power is needed to accelerate the turbocharger, which is not the case in a steady state point. When opening the throttle during a transient simulation, the turbocharger is increasing its speed due to the extra energy that comes with an increase in exhaust mass flow and temperature. When running a steady state simulation with the same criteria (the same turbospeed, air mass flow and pressure ratio over compressor) as in a time step during the transient, the excessive energy which is needed to accelerate the turbo during the transient ends up as increased mass flow through the compressor in the steady state simulation.

In Figure 5, the point A represents a transient condition experienced during a load step with the throttle fully open. The transient will end in steady state condition at point B. If using a bleed off valve to increase the compressor's power requirement at point A together with a wide open throttle, steady state condition A* will be achieved. Point A* will have similar turbine speed and pressure ratio over the compressor. The extra compressor power due to the increased mass flow in point A* will be equivalent to the power available to accelerate the turbocharger at point A during the transient.

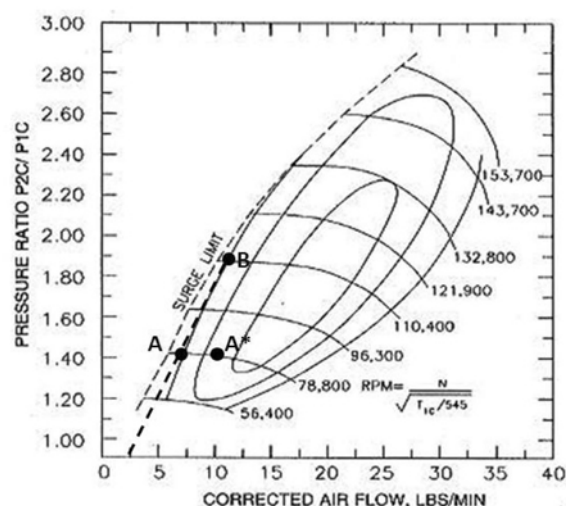


Figure 5. An overview of a compressor map [2] with the path which the compressor is taken during a transient (through A to B) and the stationary point with the same conditions (A*).

The transient for a turbocharged SI engine is situated near the surge line where the speed line is flat. To simulate point A during steady state with fully open throttle the turbo speed is fixed and the compressor can only move on one speed line in

the compressor map. After the compressor, a bypass valve is needed to bleed off the extra energy that the turbocharger uses to accelerate during a transient. A schematic picture of this bypass is shown in [Figure 6](#).

The increased mass flow is bled off with a valve after the compressor. The engine has the same speed, mass flow and boost pressure during the steady state simulation as if it were in point A during the transient.

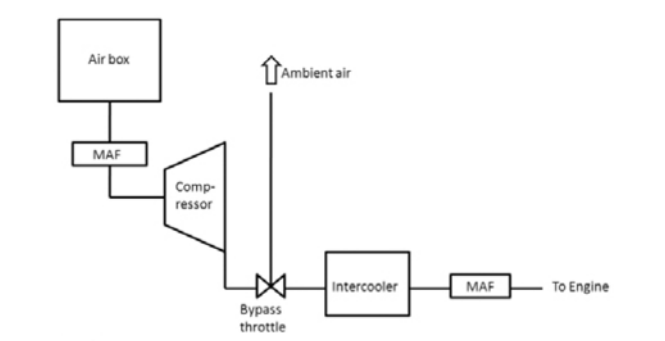


Figure 6. System schematic where the bypass is situated after the compressor and bleeds off mass flow back to open air to get rid of the excess energy.

If, for a number of time steps during a reference transient, the state of the engine is used to run a steady state DOE simulation. These steady state points can be optimized, and VNT/VVT settings are then used for that specific time mark that the steady state simulation reflects. In the DOE the parameters that have been varied are the VNT and the VVT settings in 10 steps, from fully opened to fully closed.

8 different parameters were considered to be a good measure when running the DOE:s at the different time steps:

- Turbocharger shaft torque imbalance
- Turbine efficiency
- Pressure ratio turbine
- Turbocharger shaft torque
- Engine torque
- Trapping ratio
- Volumetric efficiency times pressure ratio over turbine
- Volumetric efficiency times pressure ratio over the compressor

As can be seen above, most of the parameters are focused on the turbocharger and its speed build up, 3 parameters take the gas exchange over the cylinder in consideration and one, the engine torque, is an overall engine parameter.

To get a good reference transient for the simulation method described above a small trial and error scheme with 48

different cases where set up and simulated. [Figure 7](#) illustrates the different strategies for controlling the VNT and [table 1](#) and [table 2](#) describe the strategies for the VNT at different time steps. The resulting transient for the 48 simulated cases are shown in [Figure 8](#).

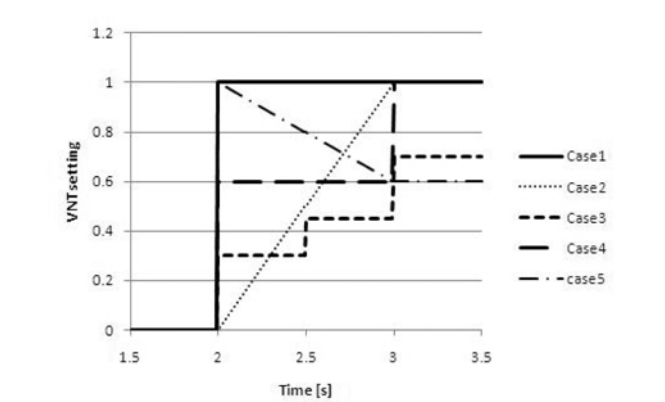


Figure 7. VNT strategies during a transient at 1750 rpm.

As can be seen in [Figure 7](#), 5 different strategies were tried. For each constant (in [table 1](#)) 4 different values were tried for the VNT. The different values for the VNT are presented in [table 2](#).

Table 1. Strategy of the VNT at different time steps, where the case number corresponds to the case number in [Figure 7](#). The letters are VNT positions at different time steps. The VNT position is altered between 4 values for each letter ([Table 2](#)).

Time	Case1	Case2	Case3	Case4	Case5
1	0	0	0	0	0
1.99	0	0	0	0	0
2	A	0	D	G	I
2.49	A	B	D	G	J
2.5	A	B	E	G	J
2.99	A	C	E	G	K
3	A	C	F	H	K
3.5	A	C	F	H	K