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Performance optimization of a spark-ignition turbocharged VVA engine under knock limited operation

Vincenzo De Bellis *

Industrial Engineering Department, Mechanic and Energetic Section, University of Naples "Federico II", via Caludio 21, 80125 Naples, Italy

HIGHLIGHTS

- 1D simulation of a turbocharged VVA engine under knock limited operation.
- Description of turbulence, combustion and knock processes by phenomenological models.
- Comparison of *Full Lift* and EIVC valve strategies at high load to improve fuel economy.
- "Virtual" calibration of an engine by the integration of 1D simulation and automatic optimizer.

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ABSTRACT

Various solutions are being proposed to improve the performance of spark-ignition internal combustion engines. A very effective approach is the *downsizing* technique, which allows the reducing of the Brake Specific Fuel Consumption (BSFC) at part load, while maintaining the required performance at high load. On the other hand, the above technique may cause substantial BSFC detrainments at high load because of the onset of knocking combustions.

In the present work, a turbocharged spark ignition engine equipped with a fully flexible valve system is numerically investigated by a 1D model (GT-Power™). Proper "user routines" are used to simulate the turbulent combustion process and the knock phenomenon. In a first stage, the engine model is validated against experimental data under both high and part load operations, in terms of overall performance and combustion evolution. The validated model is then integrated in a multipurpose commercial optimizer (modeFRONTIER™) with the aim to identify the engine calibrations that maximize the load and minimize the BSFC under high load knock-limited operations at a speed of 3000 rpm. The effects of different intake valve strategies are compared. The optimized operating parameters are the waste-gate valve opening and the air-to-fuel ratio, while the combustion phasing is automatically adjusted to avoid the knock onset. Proper constraints are assigned for the boost pressure, turbocharger speed, and turbine inlet temperature. The adopted optimization process shows the capability to reproduce the experimentally-identified calibration with satisfactory accuracy. In addition, the results underline the BSFC advantages related to an early intake valve closure strategy with respect to a *Full Lift* one, due to a better combustion phasing and a reduced mixture over-fuelling.

The developed automatic procedure allows for a "virtual" engine calibration on a completely theoretical basis and proves to be very helpful in reducing the engine development costs and time-to-market.

1. Introduction

Recent automotive internal combustion engines are characterized by more and more complex architecture in order to minimize the Brake Specific Fuel Consumption (BSFC), without deteriorating power and torque performance, and to comply with the European regulation concerning pollutants and CO_2 emissions [1]. To this aim, an effective strategy for spark ignition engines, called *downsizing*, is to reduce the total displacement and to couple a turbocharger to the engine [2–4].

As known, the engine downsizing allows for an improved BSFC at part load, mainly thanks to a reduced throttling of the intake system [2,3]. On the other hand, it does not undermine the full load performance, thanks to the possibility of increasing the intake air density by a turbocharger. However, this strategy may cause the

* Tel.: +39 081 7683264; fax: +39 081 2394165.
E-mail address: vincenzo.debellis@unina.it

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Nomenclature

A	area
C_f	skin friction coefficient
c_p	specific heat at a constant pressure
C_p	pressure loss coefficient
dx	discretization length
D	equivalent diameter, dissipation rate of turbulent kinetic energy
D_3	fractal dimension
e	total internal energy per unit mass
h	total enthalpy per unit mass
k	turbulent kinetic energy
K	mean flow energy
l_k	Kolmogorov length scale
L_I	integral length scale
L_{max}	maximum wrinkling of the flame front
L_{min}	minimum wrinkling of the flame front
m	mass
$\dot{m}$	mass flow rate
N	number of boundaries
p	pressure
P	dissipation rate of mean flow kinetic energy
Q_W	heat exchange through wall
Q_{chem}	heat released by chemical reaction in the unburned zone
Re_t	turbulent Reynolds number
t	time
t_{trans}	transition characteristic time from laminar to turbulent combustion
T	temperature
u	velocity at boundary
u'	in-cylinder turbulent velocity
U_f	in-cylinder mean flow velocity
V	volume
x_i	mass fraction of species i-th
$x_{u,knock}$	unburned mass fraction at knock event

Greeks

ρ	density
υ	kinematic viscosity
φ_2	intake valve closure angle

Subscripts

b	burned zone
ex	exhaust
in	intake
L	laminar
T	turbulent
u	unburned zone

Acronyms

1D/3D	One/Three Dimensional
BSFC	Brake Specific Fuel Consumption
BMEP	Brake Mean Effective Pressure
CAD	Crank Angle Degree
EIVC	Early Intake Valve Closure
FTDC	Firing Top Dead Center
IMEP	Indicated Mean Effective Pressure
IVC	Intake Valve Closure
LIVO	Late Intake Valve Opening
MFB_{10}	10% of Mass Fraction Burned
MFB_{50}	50% of Mass Fraction Burned
MFB_{90}	90% of Mass Fraction Burned
MOGA	Multi Objective Genetic Algorithm
PID	Proportional Integral Derivative
PMEP	Pumping Mean Effective Pressure
VVA	Variable Valve Actuation
TIT	Turbine Inlet Temperature

onset of abnormal combustion, such as pre-ignitions or knock, especially if the boost level is excessively high [5–8]. Pre-ignition most likely occurs at low engine speeds and is usually avoided by a boost limitation. Knock phenomena indeed can be controlled by delaying the combustion phasing [9]. This however penalizes the thermodynamic efficiency [10] and causes an increase in the exhaust temperature at the turbine inlet. This additional concern is usually compensated by a mixture over-fuelling, with further fuel economy penalizations [11].

Among the various paths to overcome the above issues [12–16], unconventional thermodynamic cycles, such as Atkinson [17,18] or Miller [19], represent a promising solution. The above cycles involve a lower effective compression ratio and contribute to reducing the knock tendency [20].

The calibration of a modern engine is to identify, for various points of the operating plane, the optimal values of several control parameters, such as spark timing, air-to-fuel ratio, valve strategy, turbocharger setting, and EGR level, with the aim to reach prescribed targets, such as minimum fuel consumption, minimum pollutants and CO_2 emissions. At the same time, the compliance of some constraints has to be verified, such as maximum allowable levels for in-cylinder and boost pressures, exhaust temperature, and turbocharger speed.

Because of the large number of degrees of freedom offered by modern engine architectures, the calibration process usually requires several months to be accomplished with an adequate resolution in terms of engine speed and load level. The above issue also affects the development costs of a new engine. In the light of these considerations, the possibility to perform an engine pre-calibration through numerical models would be very helpful to reduce development time and costs.

1D models have been successfully employed for several years for the design of the intake and exhaust pipes and for the definition of optimal valve strategies, as in [21,22]. In the above works, an integrated 1D model/optimizer approach is followed to investigate the influence on the engine performance of the cylinder filling and of the piping system fluid-dynamic behaviour. The combustion process is modeled by simplified approaches (un-predictive Wiebe function), since knock free operation and medium/low load conditions are considered. A more complex problem is addressed in [23,17]. In the former, different optimization algorithms are used to find the engine calibrations (throttle valve position, valve phasing and spark advance) that define the trade-off between BSFC and noxious emissions. In [17], valve strategy, throttle position, air-to-fuel ratio and spark advance are automatically modified to minimize the fuel consumption at part load. In both cases, phenomenological turbulence and combustion sub-models are used. In this way, an enhanced description of the complex interactions among the factors affecting the in-cylinder processes (turbulence production and destruction, air/fuel mixture quality, flame speed, laminar to turbulent flame transition, heat transfer, etc.) is provided.

On the other hand, in the case of turbocharged downsized engines, performance at high and full load are mainly controlled by the knock onset, which in turn influences the engine calibration, in terms of spark timing [9] and mixture quality [11]. In those cases, the adoption of a proper sub-model for the description of the knock