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A New Tool to Optimize ICE Performance and Emissions Via 1D Code Coupled with GAs

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Abstract

The aim of this paper is to propose a new strategy to optimize the performance and to reduce the emission levels of Internal Combustion Engines by varying intake valve lift profile and timing. The object of the study was an ICE – SI, GDI, 1.4 l, four cylinders, 16V, turbocharged. It was equipped with an electrohydraulic VVA system which allows the intake valves to vary, at the same time, lift and timing in order to realize early IVC and/or late IVO. Thanks to this, the engine can always operate in the optimal fluid dynamics conditions in order to achieve the best performance and emission levels. A model of the engine was implemented in GT-Power™ for several operating conditions (partial load, full load, low and high engine speed), and then coupled with a single-objective genetic algorithm, evolved subsequently into a multi-objective genetic algorithm.
Two different analysis were carried out: the first one for reducing CO_2 emissions at partial load and low engine speed (single-objective optimization), and the second one for increasing the brake torque at full load (multi-objective optimization).
The proposed model shows the possibility to quickly find optimal solutions for the test cases considered, and it let the opportunity to be further developed and improved in order to optimize many other parameters of the ICE.

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Keywords: VVA system; GAs; optimization; valve lift profile

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1. Introduction

Nowadays the ICE design process, but in general design processes for all engineering fields, is definitely dependent on CAE techniques such as CFD, FEA, CAD, CAM and son on. These techniques allow to create mathematical models of the engine in order to either entirely design it or to optimize pre-existent one. In the first case the process is obviously quite long and needs to be validate through experimental tests, on the other hand the optimization process is definitely faster because in general it needs just “few adjustments” of the mathematical model.

One common optimization technique used is based on Genetic Algorithms (GAs), which are search algorithms based on the mechanics of natural selection and natural genetics, proposed by John Holland as a heuristic method based on “survival of the fittest”. [1-3]. Currently GAs can be easily coupled with one or more CAE tools mentioned above, and thanks to their potentiality is relatively simple to find the optimal solution for the mathematical model considered.

In this paper the authors proposed a method to optimize engine parameters by coupling a GA implemented in Matlab™ with a 1D GDI – VVA engine model implemented in GT-Power™ [4], working at different operating conditions such as: 2000, 2500 r/min at partial load (respectively at about 10% and 50% compared to the maximum value of bmep); 1500, 1750 and 5000 r/min at full load. The main features of the considered engine are summarized in Table 1 while Fig. 1.a shows the comparison between the experimental and numerical data for 5000 r/min full load, normalized with respect to the maximum value of in-cylinder absolute pressure of the engine. For the sake of synthesis and space the comparison between experimental and numerical data for the others operating points was omitted.

Table 1: engine main features

Model	FIRE
Type	GDI, Turbocharged, 4 cyl., 16 valves, electrohydraulic VVA
Displacement	1368 cm^3
Bore/Stroke	72 mm / 84 mm
Compression ratio	10

Thanks to the so called “MultiAir” VVA system controlling the inlet valves, it is possible to vary both lift and timing in order to realize only EIVC, or EIVC and LIVO (Fig. 1.b) and consequently regulate the load of the engine to adapt it to the different demands of the driver. Furthermore “MultiAir” let the possibility of realizing a “pre-lift” [5-7] of the valves during the exhaust stroke to increase the overlap and either achieve internal EGR at part load to reduce NO_x emissions, or increase the volumetric efficiency at high load to maximize the brake torque. This second strategy was implemented for 1500 and 1750 r/min at full load. Exploiting the potentiality of Genetic Algorithm matched with such VVA system, it was possible to explore different configurations of the intake valves lift and timing for the operating conditions considered.

For each operating points considered, a Wiebe function, which gives the mass fraction burned versus crank angle curve, was imposed. Each of these functions was determined on the base of experimental measures, thus they already take into account the anti-knock strategies (e.g. retarded spark timing, mixture enrichment, etc.) [8].

Since the goal of the present work was to create a mathematical model which would allow the optimization of ICE, the first analysis was a single-objective optimization focused just on the reduction of

CO_2 emissions at partial load and low engine speed. The second one indeed was focused on the maximization of brake torque at full load maintaining at least the same level of CO_2.

The proposed model is found to be useful for the purpose that had been set, and results flexible because it requires just few adjustments to be further developed in order to optimize other engine parameters.

Because of obvious confidentiality reasons, the valve lift reported are normalized by the maximum value of lift, such as only the absolute variations of brake specific CO_2 and brake torque are specified as results. For other engine parameters the percentage variations were reported.

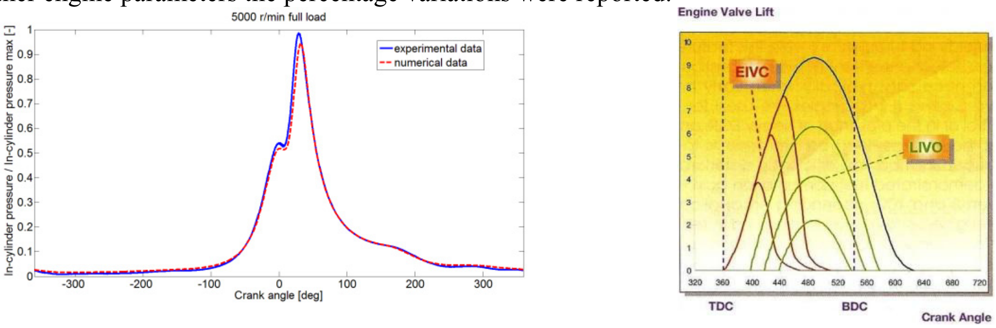


Fig.1 (a) comparison between experimental and numerical in-cylinder pressure; (b) achievable lift profiles with MultiAir VVA system [7]

Nomenclature

ai	i-th coefficient of amplitude [-]	$bsCO_2$	Brake specific fuel consumption [g/kWh]
bi	i-th coefficient of timing [-]	btq	Brake torque [Nm]
ci	i-th coefficient of shape [-]	bmep	Brake mean effective pressure [bar]
k	Number of peaks to fit [-]	θ_2	Start angle of pre-lift [deg]
y	Valve lift [-]	y_0	Pre-lift high [-]
θ	Crank angle [deg]	VVA	Variable Valve Actuation
n	Rotational speed [r/min]	LIVO	Late Inlet Valve Opening
RMSE	Root Mean Squared Error	EIVC	Early Inlet Valve Closing
EGR	Exhaust Gas Recirculation	GDI	Gasoline Direct Injection

2. Mathematical model description

The basic idea to create the mathematical model was to fit the lift profile of the valves with a parametric equation, whose parameters would have been the input for the GA. Thanks to this strategy the optimizer would be able to handle with the valve lifts, create new ones and find the optimal solution for the operating condition considered. The new valve lifts would be the input for the 1D model of the engine.

Within the GA two types of constraints were implemented: physical and numerical. The first one to ensure that all new valves lift profiles generated would follow the geometry of the cam, the second one to avoid that one or more lift profiles that worsened the original performance (CO_2 or brake torque) may be select for mating [9]. To find the parametric equations needed the Gaussian model within the Curve Fitting tool of Matlab™ was used, the equation of the model is given by:

$$y = \sum_{i=1}^{k} a_i e^{\left[-\left(\frac{\theta - b_i}{c_i}\right)^2\right]} \tag{1}$$

The valve lift profiles of the implemented engine refer to its actual operating conditions in terms of actual geometry of the cam, inertial data, spring preload, thermo-physical properties of the lubricant oil and VVA strategy [5]. All this leads the lift profiles to result slightly asymmetrical with respect to their maximum value. For this reasons different values of *k* were assumed in Eq. (1) in order to maximize the correlation factor R^2 and minimize consequently the RMSE, in particular for 2000, 2500 r/min at partial load and 5000 r/min at full load, $k = 3$; for 1500 r/min at full load, $k = 6$; for 1750 r/min at full load, $k = 8$. It means that the number of input for the GA were 9 in the first three cases, 20 in the fourth case (18 from Eq. 1 plus the start angle and high of pre-lift) and 26 for the fifth case (24 from Eq. 1 plus the start angle and high of pre-lift). Note that all fittings obtained with Eq. (1) are valid for $0 \le \theta \le 720$ and for each of them a value of R^2 greater than 0.99 was obtained.

At the end of each 1D simulation the post-processing tool of GT-Power, named GT-Post™, provided to automatically generate a text file containing the results of $bsCO_2$ and btq that would be read by GA [10]. In this way the GA was able to store and compare the variables to optimize. Figure 1.b shows the original (solid blue line) and fitted (dashed red line) lift profiles for 1500 r/min full load, while Fig. 2.a shows how the parameters y_0 and θ_2 were defined within the algorithm. For reasons of simplicity the others fitting were omitted but the results are quiet similar.

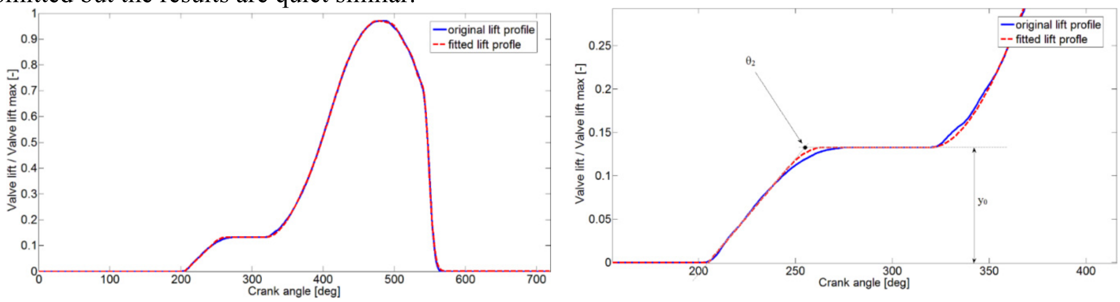


Fig. 2 (a) comparison between original and fitted lift profile for 1500 r/min; (b) start angle of pre-lift and pre-lift high explanation

Figure 3 shows how the entire optimization tool works. For the bi-objective optimization cases the GA provided also to mark all individuals that did not observe numerical constraints as unfeasible, in order to divide all individuals of the objective space into three categories: unfeasible, feasible (dominated) and Pareto front (non dominated) [9]. It is known that the performance of GAs are strongly influenced by the value of population size, number of generations and the other typical GAs' parameters [11]. Currently a depth study about these parameters were not conducted, so it took about three days to perform each simulation on a HP h8-1301el desktop, with Intel Quad Core i7-3770 processor (3.4 GHz), assuming a population size of 200 individuals and a max number of generations of 100 [12-14].

1. Geometry and case setup

The geometry of the main case is shown in Figure 3. Also two other cases as shown in this figure are considered for study about effect of the upstream corner at the end of the seat and also distance between the corner and the nozzle. Table 1 summarizes the main geometry dimensions which are used in this study.

Actually nozzle N2 is baseline and two other nozzles are selected in order to study on effect of hole distance from the sac inlet corner.

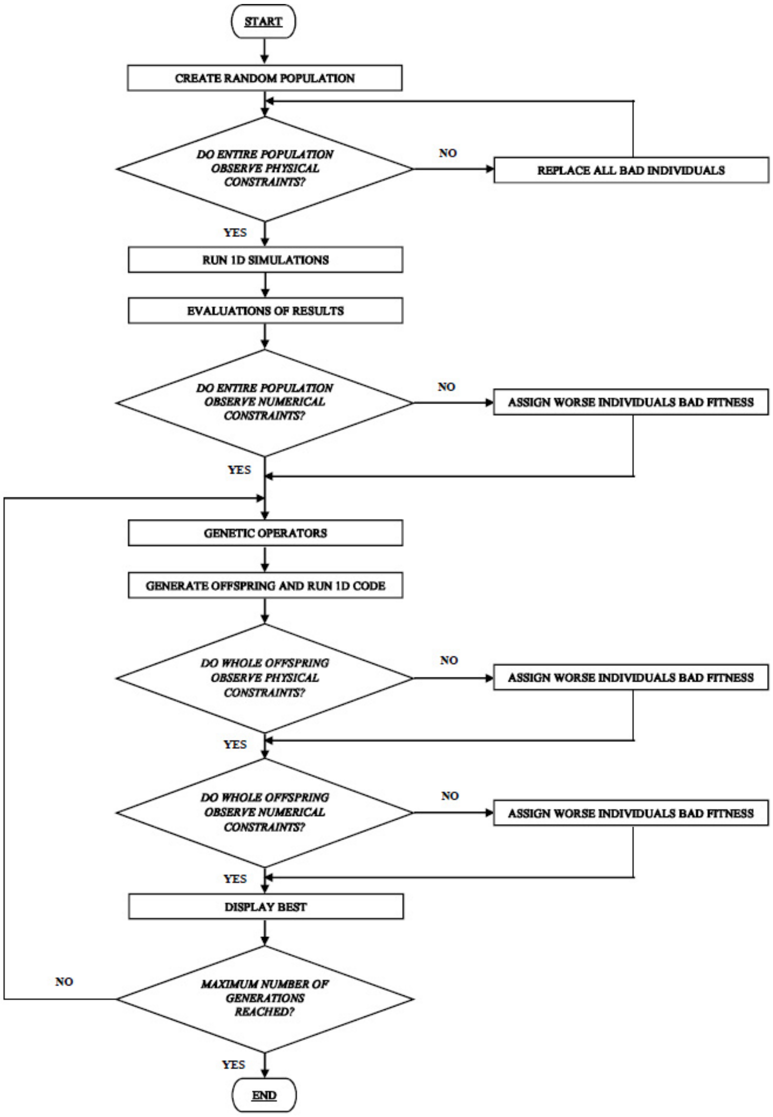


Fig. 3.: flowchart of the optimization tool

All this was probably due to the severe conditions of partialization to which the engine is subjected for this operating conditions with a very small lift profile. As shown in fig 7. the optimized lift allows the engine to "deeply breathe" and definitely to increase the work per cycle. The values of $bsCO_2$ in fig. 4.a are normalized with respect to the starting emitted level by the engine for this case. Note that the optimization process for this operating point led to an increase of bmep. Trying to maintain the original value of 2 bar, a second optimization was carried out, in which the numerical constrain imposed was just this value. In this case the GA did not achieve any improvement in terms of bsCO_2, this probably means that the valve lift was optimized yet, and a reduction of CO_2 level is obtainable just with a variation of the load.

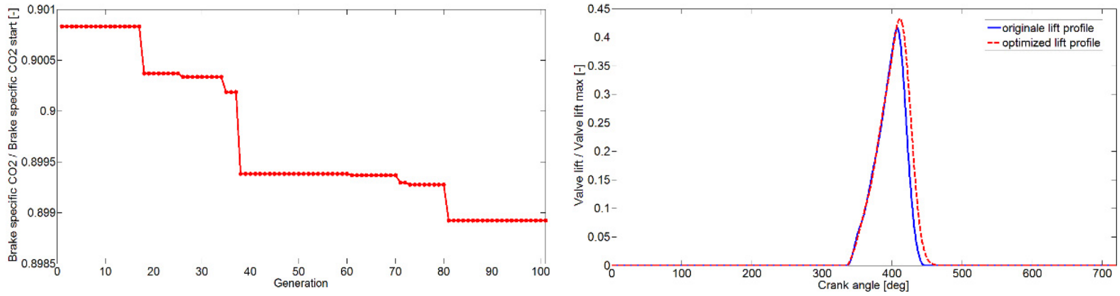


Fig. 4 (a) reduction of CO_2 vs. number of generations; (b) optimized lift profile at 2000 r/min

1.1. *2500 r/min partial load*

Even for 2500 r/min the procedure and the considerations were the same of the previous case but a reduction of just 3 g/kWh of CO_2 was realized with the GA, accompanied by an increase of brake efficiency (+0.1%) and brake mean effective pressure (+6.4%). The minor improvement compared to the 2000 r/min case was probably due to the fact that the original valve lift for this case was more similar to the maximum lift obtainable with the cam geometry, so the engine is definitely less partialized and already works consequently in a quasi-optimal condition.

1.2. *5000 r/min full load*

In this case, the valve lift is very close to the maximum lift achievable with the cam, for this reason the bi-objective optimizer was not able to find any better configuration. Fig. 5 shows that all the individuals created by GA were marked as unfeasible because they did not respect at least one of imposed physical constraints. The brake torque and brake specific CO_2 reported in Fig. 5 are normalized with respect to the starting emitted level for this case.

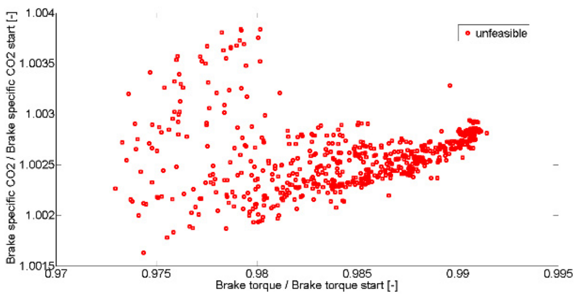


Fig. 5 objective space for 5000 r/min full load

1.3. 1500 r/min full load

As mentioned before, either for this case or for the next one, a pre-lift strategy was applied to increase brake torque. As the valve lift profile was almost at its maximum value for both cases (see fig. 2.a) it did not make sense to vary it entirely, so the only parameters that varied within the algorithm were the start angle of pre-lift and its high (see fig. 2.b). The optimized pre-lift strategy leads to a higher volumetric efficiency (+9.7%) with consequent increase of about 8 Nm of the brake torque and a reduction of 2 g/kWh of CO_2. Figures 9 and 10 show the results obtained. In particular on the top left of fig. 9 it can be noted a red square representing all individuals which did not respect at least one of imposed constraints as shown in fig. 5.

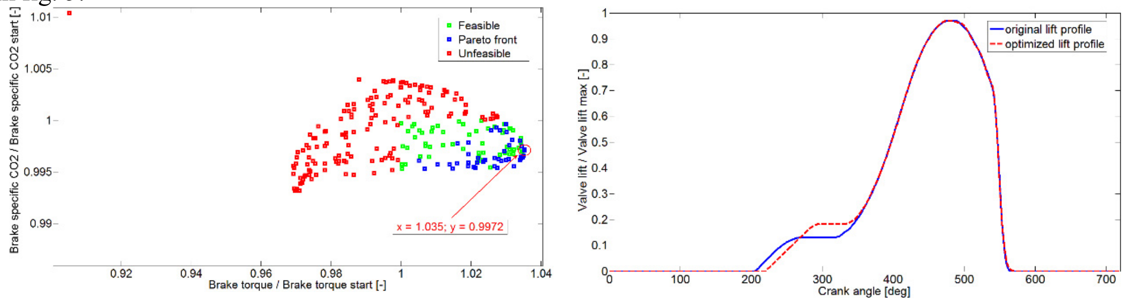


Fig. 6 (a) objective space for 1500 r/min full load; (b) optimized lift profile at 1500 r/min full load

1.4. 1750 r/min full load

Following the same procedure of the previous case, for this operating point the improvement of performance in terms of brake torque was of about 4 Nm with a reduction of 10 g/kWh of CO_2 and an increase of the volumetric efficiency of about 3%.

4. Conclusions

In the present work an optimization tool was proposed to evaluate and then improve the performances of ICE. The study was focused on a GDI engine equipped with an electro-hydraulic variable valve actuation system for the inlet valve, called “MultiAir”. This system allows to vary the inlet valve lift profile and to realize consequently different actuation strategies for the inlet valves such as late opening, early closure and a pre-lift to increase the overlap. A genetic algorithm was implemented and matched with a 1D model of the engine for several rotational speed and load, in order to find, under different constraints, new valve lift profiles which led to a reduction of brake specific CO_2 or to an increase of brake torque.

For partial load of 2000, 2500 r/min, a single-objective optimization was performed. The target of the optimization was the reduction of brake specific CO_2. The optimization process showed that by varying the valve lift profile, depending on the rotational speed considered, it was possible to obtain a substantial reduction of carbon dioxide. For full load cases at 1500, 1750 and 5000 r/min, a bi-objective optimization was carried out instead, with the aim of maximize brake torque maintaining at least the same level of brake specific CO_2. At low rotational speed an increase of brake torque was obtained exploiting the pre-lift strategy, conversely at 5000 r/min the genetic algorithm did not find any valve profile that improved the starting performances.

The optimization tool resulted adaptable for the different cases considered and it could be easily modified in order to evaluate and optimize other engine parameters. One interesting evolution of the proposed model is to extend the pre-lift strategy also at partial load, and after a proper calibration of the predictive combustion model of the 1D code, evaluate the reduction of NO_x emissions due to the internal exhaust gas recirculation.

References

[1] Goldberg D E. Genetic Algorithms in Search, Optimization and Machine Learning. Addison-Wesley; 1989.

[2] Holland J H. Adaptation in Natural and Artificial Systems. University of Michigan Press; 1975.

[3] Sivanandam S N, Deepa S N. Introduction to Genetic Algorithms. Springer; 2008.

[4] GT-Power User's Manual and Tutorial. GT-SUITE Version 7.4. Gamma Technologies Inc., Westmont, IL, USA, 2013.

[5] Ferreri P, Venezia C. UNIAIR Variable Valve Actuation System Modelling and Integration to the Engine in the GT-SUITE environment. GT-SUITE European Conference (Frankfurt); 2008.

[6] Bozza F, De Bellis V, De Masi V, Gimelli A, Muccillo M. *Pre-lift* valve actuation strategy for the performance improvement of a DISI VVA turbocharged engine. Energy Procedia 45 (2014) 819-828.

[7] Bernard L, Ferrari A, Rinolfi R, Vafidis C. Fuel economy improvement potential of Uniair throttleless technology. J. Ital. Automot. Tech. Assoc. 56 (2003) 40-49.

[8] Heywood J B. Internal Combustion Engine Fundamentals. New York: McGraw-Hill; 1988.

[9] Kalyanmoy D. Multi-Objective Optimization Using Evolutionary Algorithms: An Introduction. KanGAL Report Number 2011003, Indian Institute of Technology Kanpur; 2011.

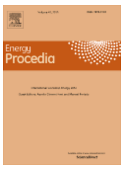
[10] GT-Post User's Manual and Tutorial. GT-SUITE Version 7.4. Gamma Technologies Inc., Westmont, IL, USA, 2013.

[11] Donateo T, de Risi A, Laforgia D. Optimization of High Pressure Common Rail Electro-injector Using Genetic Algorithms. SAE Technical Paper, SAE2001-01-1980.

[12] Mitchell M. An Introduction To Genetic Algorithms. The MIT Press, Cambridge, Massachusetts; 1998.

[13] Kim B M, Kim Y B, Oh C H. A Study of the Convergence of Genetic Algorithms. Computers ind. Engng Vol. 33, Nos 3-4, pp. 581-588, 1997.

[14] Santos A, Dourado A. Global Optimization of energy and Production in Process Industries: a Genetic Algorithm Application. Control engineering practice 7, pp. 549-554, 1999.



Biography

Dino Pirrello received the M.Sc. Degree in Mechanical Engineering from University of Catania in 2012. He is currently attending a Ph.D. in Energy System at University of Salento. His principal interesting are internal combustion engine, aerodynamics of airfoil and genetic algorithms.