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Cam Profile Optimization of a Nonlinear Valve Train Dynamic System

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Abstract: The internal combustion engines are complex and widely used equipment in automotive and energy fields. This machine has as main function the conversion of thermal energy from the fuel combustion into mechanical energy. The technological development and the increasing need of improvements such as energetic efficiency and reduction of emissions, brought many studies related to internal combustion engines in many fields of knowledge, such as thermodynamics, fuels, tribology, materials, manufacturing, vibrations and dynamics. In the dynamics of mechanisms subject, many studies related to the slider-crankshaft and the valve train systems are of higher importance in the development and optimization of this equipment. The main objective of this work is to present a study related to the optimization process of a cam profile and its effects in the dynamic behavior of the valve train system. To accomplish this purpose, it was used a real cam of a mono cylinder engine with an overhead valve system. The cam profile of this system was measured and optimized searching the minimization of the root mean square (RMS) values of acceleration of the valve applied in a nonlinear dynamic model, using a hybrid optimization methodology, using sequential quadratic programming (SQP) and genetic algorithms. The simulation results show a global reduction in the residual accelerations generated by the closing of the valve, when compared with the behavior of the original cam profile.

Keywords: Cam, Optimization, Valve train, Dynamic, Nonlinear

INTRODUCTION

Internal combustion engines are widely used equipment in automotive and energy fields and there is a constant need of scientific and technological development and increasing of energy efficiency and reduction of emissions, leading to the development of research in different areas of knowledge, such as fuels, tribology, thermodynamics, materials, manufacturing, dynamics and vibrations. Research in the dynamic of mechanism field of study, applied to valve train system, can contribute to reduce engine vibration level, fuel consumption and gas emissions.

The main purpose of the valve train system is to allow the fuel air mixture to enter the combustion chamber at the time of the intake and the exhaust gas from combustion during exhaustion. There are several types of valve train systems, some of which are shown in Fig. 1. In these systems, a camshaft rotates synchronously with the engine crankshaft and drives the intake and exhaust valves. In modern and high-performance engines, the camshaft is positioned on the engine head (OHC - Over Head Camshaft), making it possible to construct a more compact and stiff assembly (Types I, II, III and IV). The valve train Type V (OHV - Over Head Valve) allows the camshaft to be located in the block and the valve is pushrod-actuated, however, due to its low stiffness, is usually used on lower rotating engines.

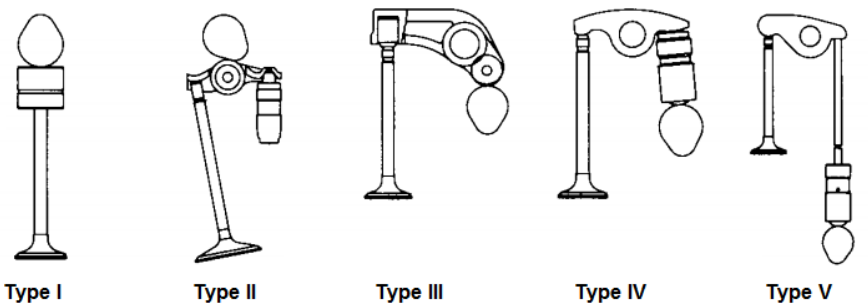


Figure 1 - Different types of valve train systems (Wang, 2007)

In this paper, it will be presented a study related to the optimization process of a cam profile, aiming the improvement of the dynamic behavior of the whole mechanism, but more specifically to the process of opening and closing of the valves during the engine running cycles. To achieve this purpose, the OHV system of a real single cylinder, 4-stroke, 10 HP Briggs & Stratton engine was used to develop the physical and mathematical models for dynamic simulation. The original cam profile of the mechanism was experimentally identified in a metrology test rig and an identification process of mass, stiffness and damping coefficients of the valve train components was performed, based on Norton (2009) guidelines.

Figure 2 shows an exploded view of the main piston-connecting rod-crankshaft and valve train systems of the 10 HP Briggs & Stratton engine (Briggs & Stratton, 2009).

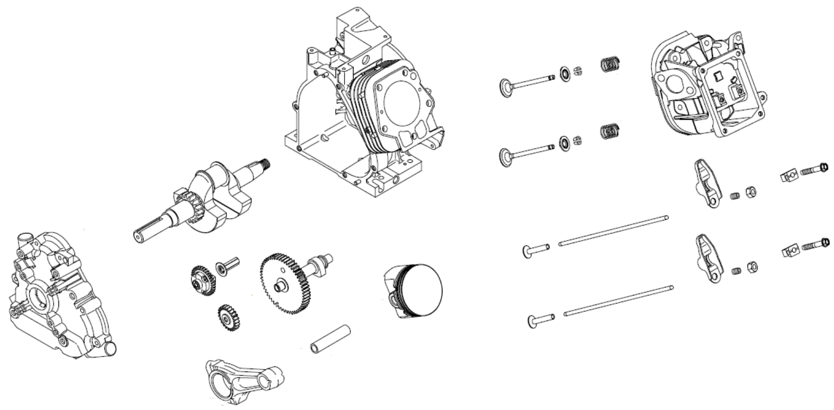


Figure 2 - Exploded view of slider-connecting rod-crankshaft and valve train systems (Briggs & Stratton, 2009)

A basic lumped parameters dynamic model of the valve train system is proposed by Norton (2009) and a procedure for the determination of dynamic coefficients (mass, stiffness and damping) is also presented; however, this model do not consider the valve-seat nonlinear effects due to the opening and closing valve movements. Tomoyose (2013) built a 5 degree of freedom (DOF) dynamic model of a 4 stroke OHC diesel engine, including hydraulic tappet model and the nonlinear contact behavior between some valve train components and in valve-seat contact. Guo, Zhang and Zou (2011) studied the behavior of a valve train system with 6 GDL and nonlinear contacts, as well as considering the angular and linear displacement of the camshaft. Andreatta and Pederiva (2014) considered a 6 DOF spring in a valve train model to analyze the system operation in low and high rotation frequency and predicting the contact losses in the mechanism.

Recent researches have been applying optimization algorithms in order to find optimal shape designs of various mechanical systems. Lampinen (2003) applied genetic algorithms to minimize force fluctuations in a valve mechanism operated by a cam device. The cam shape was represented with B-splines with control points that were obtained through the optimization procedure. Qiu et al. (2005) proposed a universal approach to optimize the cam shape using either kinematics or dynamics approaches. In the dynamic approach the authors used B-splines to represent the shape of the cam and a complex search algorithm to minimize the peak acceleration of the follower obtained through a simple numerical simulation. Salsa Junior and Pederiva (2014) applied the heuristic optimization method of differential evolution, developed by Storn and Price (1995), in the exhaust valve's dynamic response when the cam is parameterized by its acceleration curve. This method differs from other nondeterministic applications because it doesn't have a biological conception; on the contrary, it is purely mathematical, based on vector operations.

Sonmez (2007) used a direct search simulated annealing algorithm to optimize bidimensional structures subjected to quasi-static loads and restraints. This kind of algorithm simulates the behavior of materials during the heating and cooling in annealing heat treatments to find optimal solutions. The author exemplified the methodology in different structures using finite element simulation. Albers et al. (2009) used genetic algorithms in order to perform a multi-objective optimization of the shape of a crankshaft represented via spline functions. The authors emphasized the idea of integrating this design optimization with simulation results provided from CAE tools (Computer Aided Engineering) in order to have a rapid innovation framework. Bataller et al. (2018) made a kinematic study of the mandibular movement in order to propose a device for the treatment of obstructive sleep apnea. The shape of two cams of the device were optimized using evolutionary algorithms aiming to minimized the error between the cam path represented by Bezier curves and the desired one obtained in the kinematic analysis. The proposed methodology was applied to design this kind of device to a real patient.

These papers illustrate different approaches for shape optimization in distinct applications. This fact shows the broad applicability of optimization algorithms to engineering problems.

In the present paper, a dynamic model of an OHV valve train system with valve-seat nonlinear contact was developed and simulated for the cam profile optimization purpose (Cabo, 2017). For the optimization of the cam profile, it was used a combination of a genetic algorithm and a sequential quadratic programming (SQP), based on the optimization procedure proposed by Lampinen (2003). Mixing a heuristic and a classical class of optimization turned it into a more precisely improvement of the cam dynamics. As the genetic algorithm has a global approach it can search more combinations of solutions to the profile and then the sequential quadratic programming will check if the genetical found the best option available in a certain group of solutions. The optimization algorithm works in parallel with the MatLab-Simulink dynamic model, each solution provided by the genetic algorithm or the sequential quadratic programming is simulated into the nonlinear model and its results are checked by the algorithm to determine which solution has the best behavior regarding to the RMS acceleration of the valve. Therefore, the optimization process can be based on the valve acceleration itself, instead of the cam parameters.

METHODOLOGY

Dynamic modeling of valve train system

As stated in the introduction section the valve train system studied is an OHV system of a real single cylinder engine, which basics components are the cam, tappet, pushrod, rocker, valve and valve spring. The masses of the components were measured and the dimensions and geometry of these components were collected and modeled in a CAD system (Autodesk Inventor 2013). An assembly drawing of the valve train system is presented in Fig. 3(a).

Afterwards, applying the finite element method (FEM) to each one of these component, it was possible to simulate the deformation of each component due to known forces to achieve its linear stiffness coefficient. Figure 3(b) illustrates the FEM simulation of the main valve train components.

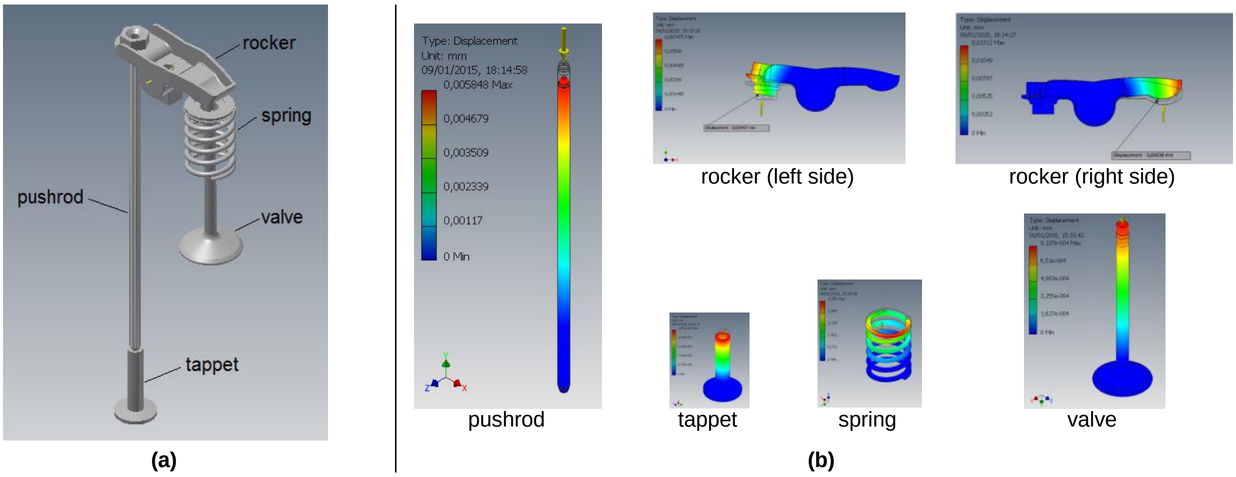


Figure 3 - (a) CAD model of the valve train system, (b) FEM simulation of the valve train components

The left and right rocker masses coefficients were defined as equivalent translational masses, considering the corresponding rotating inertia and the rocker dimensions. Based on the stiffness (k) and mass (m) coefficients, the corresponding values of the damping (c) coefficients were estimated, assuming that the damping coefficients are 5% of the corresponding critical damping ($c_c = 2\sqrt{km}$), based on guidelines provided by Norton (2009) for steel and aluminum alloys, as expressed in Eq. (6):

$$c = 0.05c_c = 0.1\sqrt{km} \tag{6}$$

The mass, stiffness and damping coefficients of valve train components were applied to draw up the dynamic model with five DOF presented in Fig. 4, where the displacements (x) and mass (m), stiffness (k) and damping (c) coefficients are associated to the following elements: camshaft (c), tappet (t), pushrod (p), rocker (r), left side (a), right side (b), spring (s) and valve (v) (Celso, 2007).

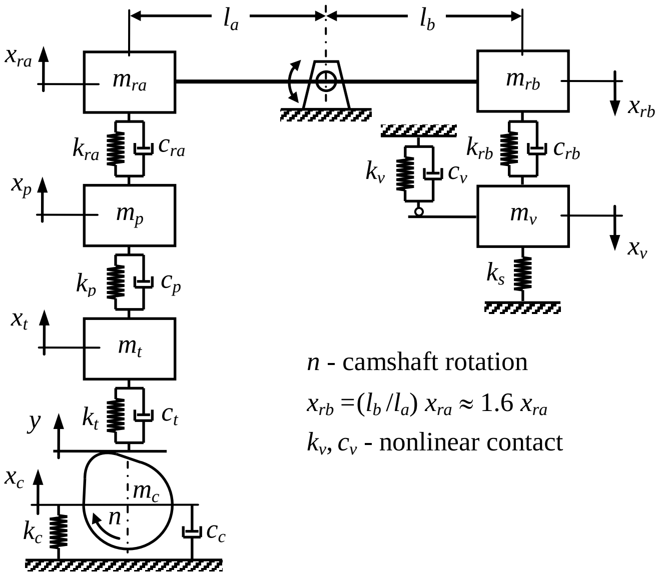


Figure 4 - Dynamic model of the valve train system

The dynamic equations of the dynamic model were obtained, Eq. (1 - 5), and a simulation module was created in MatLab-Simulink software to describe the system displacements, considering for the input the cam profile with a rotation n = 2000 rpm and the nonlinear valve-seat contact.

$$m_c\ddot{x}_c = -k_c x_c - c_c\dot{x}_c - k_t(x_c + y - x_t) - c_t(\dot{x}_c + \dot{y} - \dot{x}_t) \tag{1}$$

$$m_t\ddot{x}_t = -k_p(x_t - x_p) - c_p(\dot{x}_t - \dot{x}_p) - k_t(-x_c - y + x_t) - c_t(-\dot{x}_c - \dot{y} + \dot{x}_t) \tag{2}$$

$$m_p\ddot{x}_p = -k_{ra}(x_p - x_{ra}) - c_{ra}(\dot{x}_p - \dot{x}_{ra}) - k_p(x_p - x_t) - c_p(\dot{x}_p - \dot{x}_t) \tag{3}$$

$$m_{ra}\ddot{x}_{ra} = -k_{ra}(x_{ra} - x_p) - c_{ra}(\dot{x}_{ra} - \dot{x}_p) - k_{rb}(l_b/l_a)(x_{rb} - x_v) - c_{rb}(l_b/l_a)(\dot{x}_{rb} - \dot{x}_v) \tag{4}$$

$$m_v\ddot{x}_v = -k_{rb}(x_v - x_{rb}) - c_{rb}(\dot{x}_v - \dot{x}_{rb}) - k_s(x_v + x_v^*) + F_v(x_v) \tag{5}$$

In Eq. (5), x_v^* correspond to the static deformation of the spring due to assembly preload and $F_v(x_v)$ represents the nonlinear valve-seat contact force, whose behavior depends on the direction of displacement x_v of the valve:

$$F_v(x_v) = \begin{cases} 0 & \text{if} \quad x_v > 0 \\ k_v x_v + c_v\dot{x}_v & \text{if} \quad x_v \leq 0 \end{cases} \tag{6}$$

The mass, stiffness and damping coefficients of the valve train model are presented in Tab. 1, for each one of the system components.

Table 1 – Dynamic coefficients of the valve train components

Valve train component	**Mass** [g]	**Stiffness** [kN/m]	**Damping** [Ns/m]
camshaft	621	141,170.0	98.1
tappet	20	268,660.0	135.4
pushrod	10	8,549.7	23.7
rocker (left side)	23	8,549.7	7.3
rocker (right side)	9	5,588.3	5.1
spring	---	9.1	---
valve	34	61,455.0	14.9

The mathematical model of the five DOF valve train system was implemented in MatLab-Simulink, allowing de time simulation of the dynamic system, considering as input variables the cam profile and the camshaft rotation. The original cam profile was measured to identify its rise-dwell-fall-dwell cycle characteristics.

Shape optimization methodology

In order to update the profile of the cam with respect to the measured one, a hybrid optimization algorithm was used to minimize the vibrations on the valve. The cam profile was represented with spline functions which was parameterized using N_p control points p_1, p_2, ..., p_{Np} between each relevant trajectory of the system. The optimization algorithm was used to search for the optimum control points that define the geometry of the profile. Figure 5 illustrates the representation of a rise from 0 to 30 mm between 0 and 90° using a spline function with two control points.

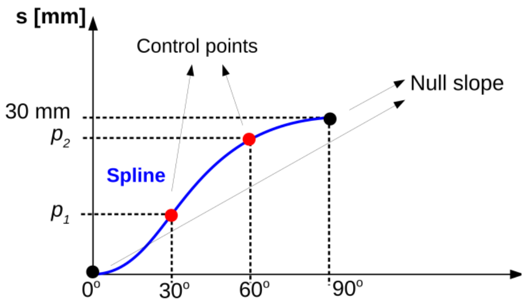


Figure 5 - Representation of the cam path using spline functions

In order to find the optimal shape of the cam it is necessary to define an objective function (OF) that represents the problem to be solved. A single OF $J(\boldsymbol{p})$ was used in this paper based on the root mean square (RMS) value of the valve acceleration ($\ddot{x}_v$):

$$J(\boldsymbol{p}) = \sqrt{\frac{1}{N}\sum_{i=0}^{n}\ddot{x}_v^2(\boldsymbol{p})} \tag{7}$$

where $\boldsymbol{p} = [p_1, p_2, \ldots, p_{Np}]$ is a vector with the control points used to represent the cam profile and N is the number of samples of the valve acceleration signal. The output response of the valve was calculated using the dynamical model of the mechanical system in a way that the acceleration is dependent on the shape of the cam represented by the vector $\boldsymbol{p}$.

In order to find the optimal solution $\boldsymbol{p}$ that can minimize the valve vibrations it is necessary to use some solution strategy. Since for this case an exhaustive search is computationally expensive due to the huge number of possible combinations in the response vector p, an optimization algorithm should be employed. In this paper a hybrid optimization strategy was used composed by a genetic algorithm (GA) and a sequential quadratic programming (SQP). The GA is a stochastic search algorithm based on the Darwin evolution theory (Michalewicz, 1996). In this strategy, the candidate solutions are named chromosomes or individuals which have their genetic material that carries the information of a possible solution to the optimization problem. These solutions are generally represented with a vector of binary numbers. The population of solutions is firstly randomly generated and their capability of solving the problem (fitness) is evaluated with the OF. The GA tends to select the best individuals to reproduce and exchange genetic materials with other candidates in the crossover phase. After that, in the mutation phase, a few individuals are selected to suffer the mutation of their genetic material. This is done to add genetic variability and exploring new solutions for the optimization problem. The newly generated population is again evaluated with the defined OF, and the selection, crossover and mutation phases are repeated until reaching the stopping criteria.

The GA can be used to find globally optimal solutions since it is not based on the calculation of the gradient of the OF. However, a possible issue of the GA is that due to the stochastic nature of the algorithm it cannot precisely find the zero-gradient solution of the optimization problem. Assuming that the answer provided by the GA is near the region of the globally optimal solution, a SQP algorithm was applied using the best solution found by the GA as initial guess. This was done in order to run a local search to refine the results of the GA to a possible global optimum solution. The proposed strategy is depicted in Fig. 6.

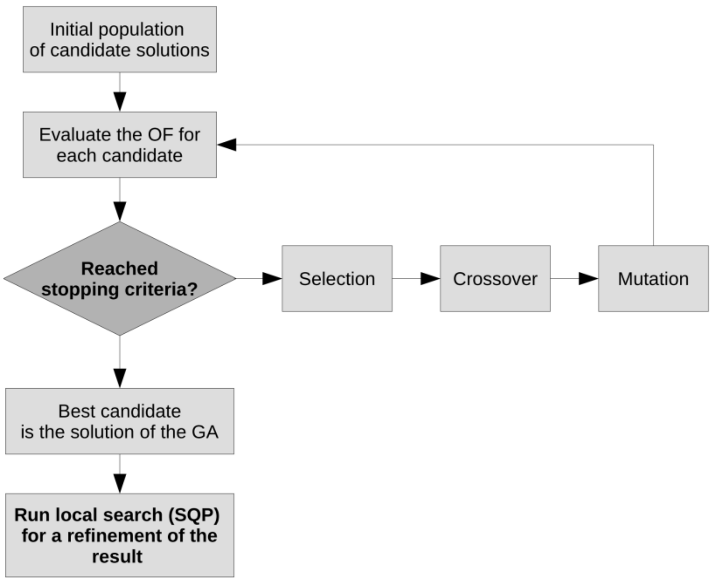


Figure 6 - Optimization strategy to define the profile of the cam

RESULTS

The hybrid optimization previously presented was applied for the cam shape design. The optimization was implemented using MATLAB R2016b The parameters of the optimization were configured as showed in Tab. 2. More information on these values can be found in Michalewicz (1996) and Luenberguer and Ye (2008).

Table 2 – Configurations of the optimization algorithm

Optimization parameter	Value
Population size (GA)	100
Number of generations (GA)	200
Selection type (GA)	Tournament
Crossover rate (GA)	80%
Mutation rate (GA)	1%
Step size stopping criteria (SQP)	1,00E-14
Function change stopping criteria (SQP)	1,00E-10
Maximum number of iterations (SQP)	1000

Due to the random nature of the GA, the code was executed 10 times and the best results are illustrated in this paper. Despite of this, it was observed that results presented little different which shows that the results found are likely to be close to the global optimum. Figure 7 shows the evolution of the OF during the execution of the GA followed by the SQP optimization. The GA stopped with the maximum number of iterations allowed (200 generations) while SQP stopped with 44 iterations due to reaching the step size tolerance. This figure also shows the importance of this hybrid approach since a significant improvement in the OF was observed with the SQP algorithm.

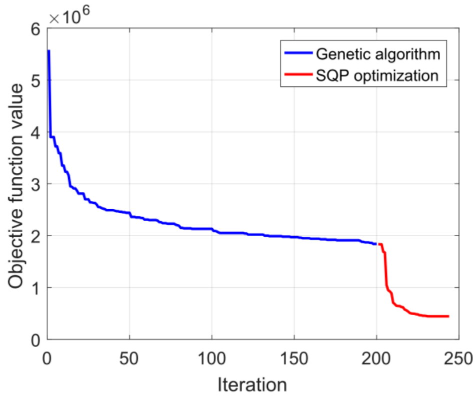
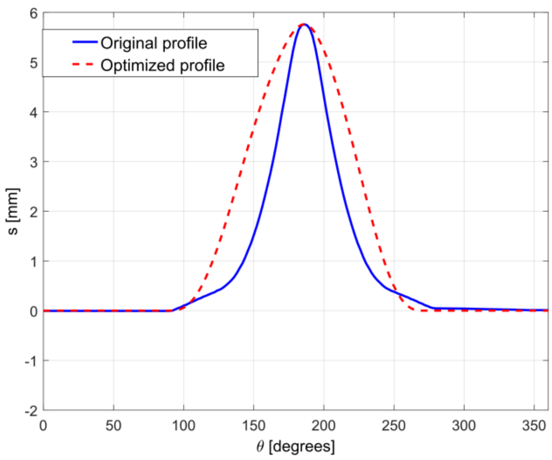


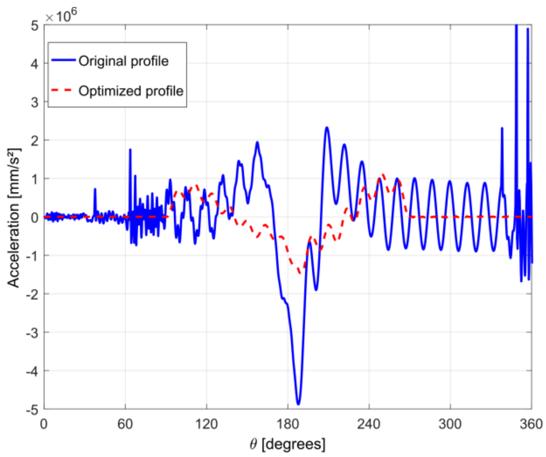
Figure 7 – Evolution of the objective function value for the GA and the SQP algorithms

The profile of the cam optimized by the hybrid algorithm is presented in Fig. 8a. As it can be seen the optimized profile has the same specified points as the original. In other words, its opening, closing and maximum point occurs at the same angle than the original profile. In addition, it has an area under the curve higher than the original one. It means that this cam allows an entrance of more fuel and air during the cycle than the other one. However, the best solution generated has not a symmetric profile.

The comparison of the valve acceleration in the critical opening and closure time interval is illustrated in Fig. 8b. It is possible to observe that the optimized shape of the cam has significant less oscillations in the valve since the RMS level of this signal was employed as the OF of the optimization. As it can be seen the optimized cam profile represented in red has a higher acceleration at the ending of the profile than the original one. However, that happens to avoid the rebatement as it can be seen in blue after 300°. Another observation that can be done is about the amplitude during the cycle of the cam. It is significantly smaller than the original model.



(a) Comparison between the original and optimized cam profiles



(b) Comparison between the acceleration of the valve according to the cam profiles

Figure 8 – Comparison between the performance of the original and the optimized profiles

CONCLUSIONS

In conclusion, in this work, it was possible to verify that, the optimization process in the cam profile focusing on the valve acceleration had good results, reducing the maximum amplitude of acceleration, the vibration after the closing of the valve due to bouncing and increasing the area below the curve. In other words, improving the amount of air and gas into the cylinder. However, the optimization process generated a profile which is not symmetric. Therefore, more studies can be done attempting to create a cam which has the same results and be symmetric. Furthermore, in further studies, other approaches can be used inserting other nonlinearities to the dynamic model of the valve train system, or changing the optimization code, using another optimization method or changing the equations to generate the profile.

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