Simulation and Analysis of the Actuation System in a Camless Piston Engine

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Abstract

This work provides a physical simulation scheme for a camless engine. The system is composed by a four stroke spark ignited cylinders and a hydraulic system which control the position of the intake/exhaust valve. The main purpose of the work is to provide a tool to analyze the mechanical behavior of the engine components and the directional valves and double acting cylinders in charge of the opening of the intake/exhaust valves as well as the control algorithm. The simulation is useful to define the dimension of the hydraulic system parameters depending on the mechanical characteristics of the engine.

Keywords
Engine, Camless, Internal combustion, Hydraulic actuation and Multisystem simulation.

1. Introduction
Automotive industry is important in a worldwide economic context. Currently, the demands on the automotive industry to keep fuel consumption low and emissions regulations constantly updated have caused this sector to be in constant search of alternative solutions to maintain its competition in the market. The growth of the production of hybrid and electric vehicles in recent years is noticeable, but currently the internal combustion (IC) engine is still the predominant mechanical power source for commercial vehicles. Moreover, it is important to analyze the entire production chain to reach the conclusion that such development is not enough, since the production of both of alternative vehicles as well as the electrical energy they consume depends on processes with highly polluting emissions, [IEA, 2020].

In an effort to hold the arising constraints related with emissions of vehicles, the increasing price of fuel and the alternative energy comp, producers are continuously developing technology advances to improve the performance of IC engines. For instance, the carburetor has been replaced to fuel injection technology in order to give control to the fuel distribution and to optimize the engine operation to different load and speed conditions, [Gillella and Sun, 2011].

Air management plays an important role in the improvement of fuel consumption and control of emissions of an IC engine. The conventional intake/exhaust valve actuation is made by means the camshaft which is connected directly to the crankshaft. Despite of being a simple and reliable mechanism, it does not offer flexibility in its operation, [Heywood, 2018].

Variable Valve Actuation (VVA) can be realized based on camshaft modifications allowing improvements on the performance and efficiency of the IC engines by means of the variation of the valve lifting, duration, time of operation or a combination, [Gillella et al., 2014]. In [Jankovic and Magner, 2002], a review on the modeling and control algorithms for Variable Cam Timing (VCT) is provided.

Different VVA techniques such as Variable Valve Timing (VVT), Variable Valve Duration (VVD) and Variable Valve Lift (VVL) with their actuation variations are studied in [Lou and Zhu, 2020]. Improvements to the VVT techniques are analyzed in [Ganbold et al., 2010], a multi-parametric model predictive control for VVT's is proposed in [Lee and Chang, 2017]. In [Pournazeri et al., 2018], a VVA technique based on genetic algorithms is proposed to improve the energetic efficiency of a IC engine. However, all the improvements mentioned before have a limited flexibility since they are constrained by the camshaft position.

To offer high flexibility in the valve-train performance, camless engines have been studied in different works, [Ashhab and Levin, 2000a], [Ashhab and Levin, 2000b], [Stefanopoulou, 1996]. The main idea is to substitute the camshaft with electronic control equiped with a set of sensors and actuators at the valve-train, allowing to integrate the advantages of several camshaft based technologies according to the operating conditions of the engine including advanced combustion techniques. This technology promises a reduction in the necessary space, a variable system with greater control, but above all a reduction of approximately 18% of mechanical losses existing in conventional IC engines, [Tormos et al., 2020].

This work is devoted to develop a simulation tool in order to define the main parameters in the actuation system for a camlees engine. The simulation works with an Electro-Hydraulic Valve Actuation (EHVA), the system consists in the control of pressurized fluid in order to ensure the correct positioning of the intake/exhaust valves. The Matlab Simscape toolbox is used in order to realize the physical modeling of the camless motor.

The paper is organized as follows: Section 1 provides a brief Introduction. In section 2 the mathematical models of the engine and the hydraulic actuation system is studied. The open-loop simulation of a single cylinder engine is analyzed in Section 3. An extension to a four cylinder engine is provided in Section 4 and finally some conclusions and future expectations on the topic are stated in Section 5.

2. Simulation Model for the Cylinder Activation

First, a single cylinder engine is used to define the main parameters involved in the IC engine and to compute the variables involved in the intake and exhaust processes and their relation with the hydraulic actuation system. The single cylinder IC engine equipped with a set of sensors and actuators is shown in Fig. 1. In the following, a detailed description of the subsystems involved in the process is provided.

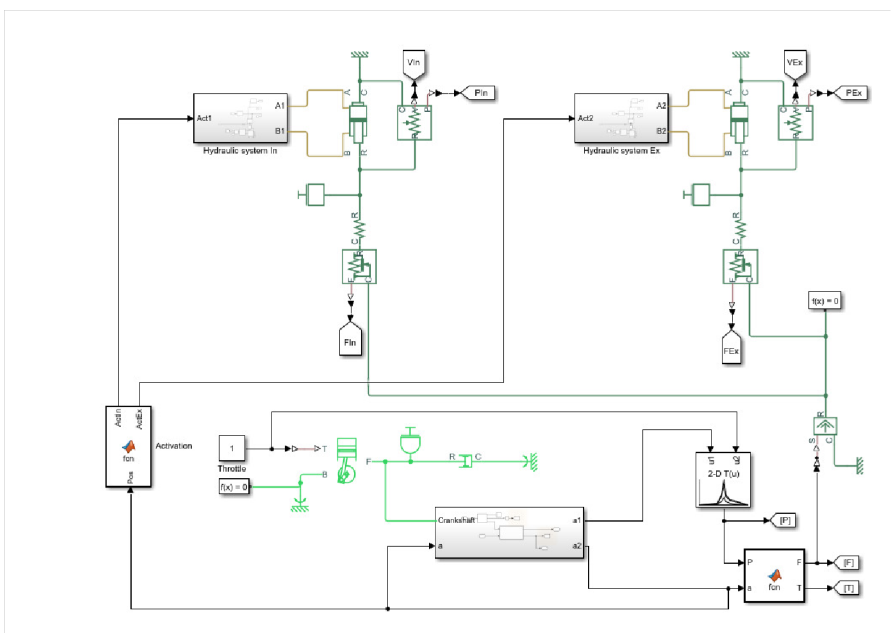

Figure 1: Physical simulation model for a camless engine with hydraulic actuation

2.1 IC Engine

A piston engine block is employed for the simulation. The piston is a four stroke engine ignited by spark. The piston has a bore $B = 0.1m$, a stroke of $S = 0.06m$, and a rod length $r = 0.1m$. The combustion related parameters are parametrized by a 2-D look up table which relates the crank angle and the throttle valve position with the output pressure in the piston, Table 1.

The crank is equipped with a position sensor and is connected along with the information of the throttle position to a look-up table Simulink block in order to perform a linear point-slope interpolation method and compute the cylinder pressure as a signal depending on the crank position.

Table 1: Pressure parametrization of the piston engine [bar].

Crank position [^{o}] \ Throttle position	0	0.3	0.8	1.0
-360	0	0	0	0
-90	0	0.9	2.4	3
-30	0	6	16	20
10	0	15	40	50
30	0	6	16	20
90	0	3	8	10
160	0	2.4	6.4	8
360	0	0	0	0

The pressure signal is used to compute the cylinder force according with:

$$F = \frac{\pi B^2}{4} (P - P_{surr}), \tag{1}$$

and the torque of the cylinder:

$$T = FS \left(\sin(\alpha) + \frac{r \sin(2\alpha)}{2\sqrt{1 - r^2 \sin^2(\alpha)}} \right), \tag{2}$$

where $\alpha \in [0°, 720°]$ is the crank position along the engine cycle and P_{surr} is the pressure in the surrounding of the cylinder.

2.2 Valve Actuator

Let us consider a hydraulic system to actuate the intake and exhaust valves. Double acting cylinders provides the force to open and close the valves. A 4/3 directional electro valve is used to control the timing, duration and position of the engine valves.

The flow and pressure of the hydraulic actuators is provided by means of a fixed displacement pump. The simulation allows to estimate the design parameters of the complete hydraulic actuation system according to the engine requirements as well as the operation conditions.

The model of the hydraulic actuator is obtained based on the free-body diagram shown in Fig. 2. The dynamical equations of the valve are given below by:

$$m\, \ddot{x}_{valve} + b\, \dot{x}_{valve} + k\, x_{valve} + F_{spring} = P_1 A_1 - P_2 A_2, \tag{3}$$

where m represents the sum of the piston mass and the valve mass, b is the friction coefficient and k is the stiffness coefficient of the valve. The position of the valve is denoted by x_{valve} with their first and second derivative being the velocity and acceleration of the valve, respectively. F_{spring} is force provided by the pre-loaded spring of the valves.

The pressures $P1$ and $P2$ are the pressures in the forward and return chambers of the double acting cylinder, with surface area $A1$ and $A2$, respectively. The pressure at the chambers are given by:

$$P_1 = \frac{\beta_e}{V_1} \int Q_1 - A_1\, \dot{x}_{valve} - C\,(P_1 - P_2),$$ (4)

and

$$P_2 = \frac{\beta_e}{V_2} \int -Q_2 + A_2\, \dot{x}_{valve} + C\,(P_1 - P_2),$$ (5)

with line volumetric flows given by:

$$Q_1 = C_d\, A_0 \sqrt{\frac{2}{\rho}\,(P_s - P_1)},$$ (6)

and

$$Q_2 = C_d\, A_0 \sqrt{\frac{2}{\rho}\,(P_s - P_2)},$$ (7)

Where β_e is the bulk modulus of the hydraulic flow, the instantaneous volume of the chambers $V1$ and $V2$, a leakage coefficient C, the density of the fluid ρ, the orifice area of the valve $A0$ and the supply pressure P_s.

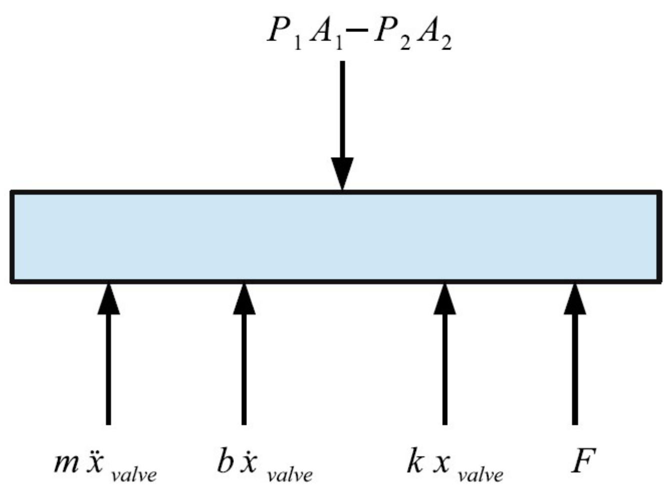

Figure 2: Forces acting over the valve.

3. Open Loop Simulation

The position of the crankshaft is measured to define an open-loop activation sequence for the hydraulic actuator. Fig. 3 shows the activation of the intake and exhaust valves over a cylinder four stroke cycle, namely for $\alpha \epsilon$ [-360°, 360°]. The hydraulic system is fed with a constant pressure source of $100MPa$. The valves have a $11mm$ stroke and their position and the forces exert-360d from the cylinder to the valves are displayed in Fig. 3.

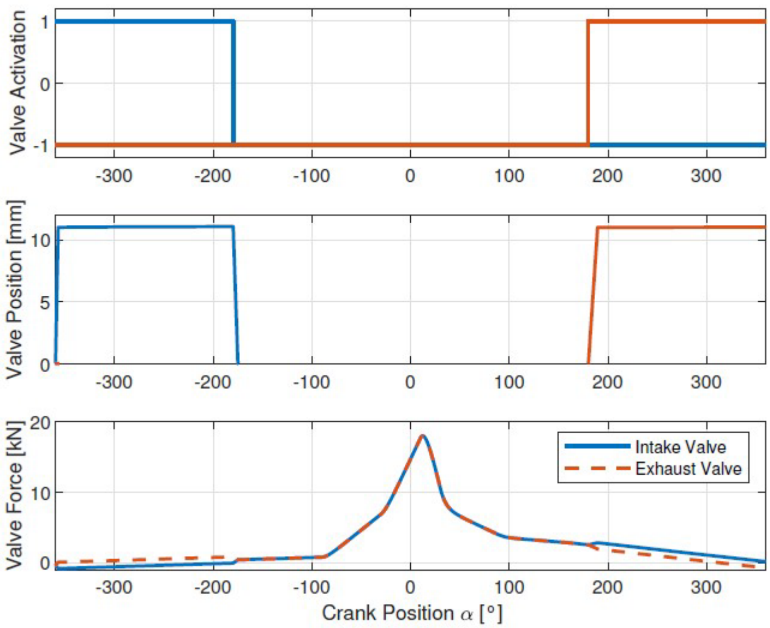

Figure 3: Valve activation over a cylinder cycle.

The numerical interpolation presented in the previous section allows to compute the mechanical variables of the cylinder which are shown in fig. 4 by considering a full throttle operation.

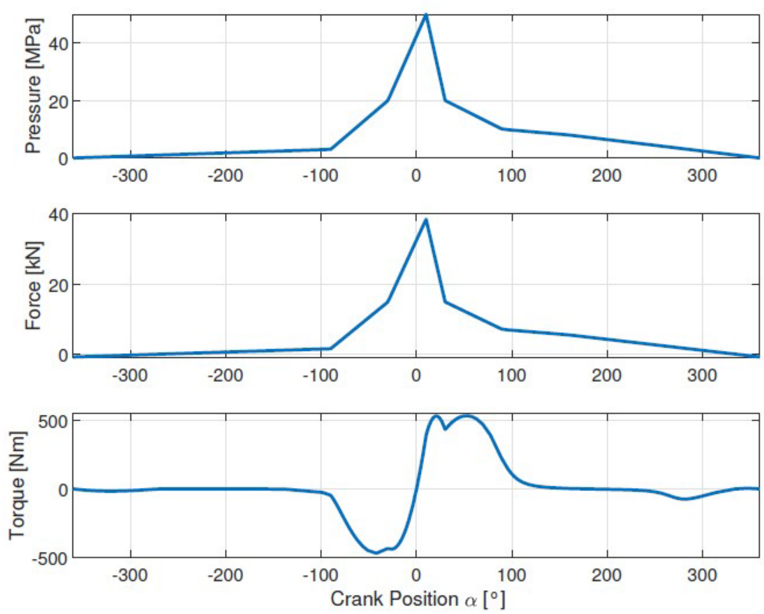

Figure 4: Cylinder pressure, force and torque.

4. Camless Four Cylinder Engine

In this section, a four cylinder in-line engine is simulated to analyze the activation of the intake valves. The position of the valves and the forces exerted by every cylinder are shown in Fig. 5.

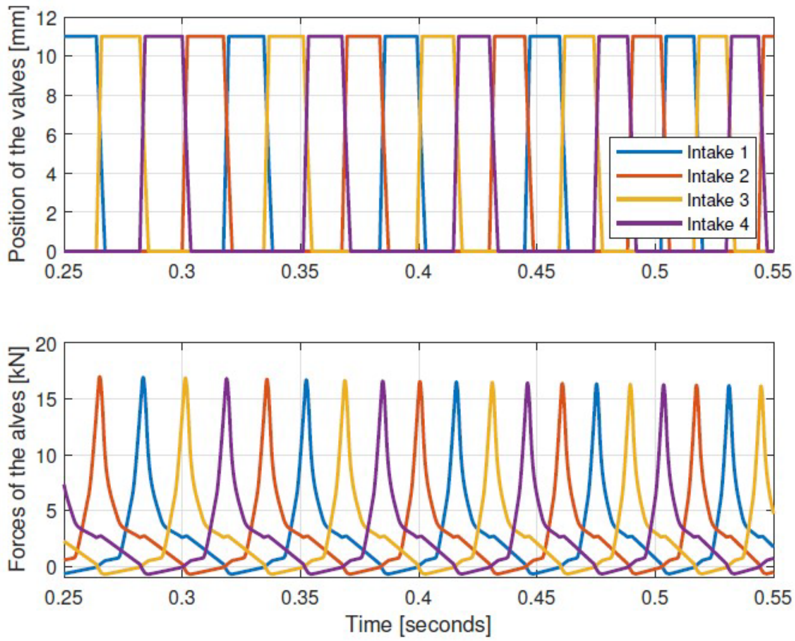

Figure 5: Activation sequence of the camless engine.

Finally, a comparison between the single cylinder engine and the four cylinder in-line engine performance, specifically the crankshaft velocity measures in rpm is shown in Fig. 6, both at full throttle.

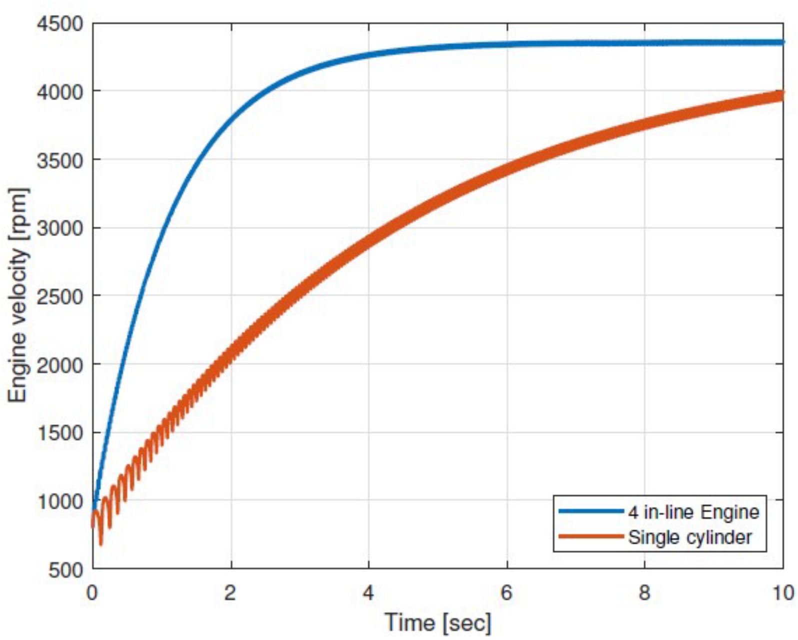

Figure 6: Comparison between the single cylinder engine and the 4 in-line cylinders engine.

5. Conclusion

A useful tool to simulate and analysis of the mechanical response of IC camless engines. The open-loop simulation provides an activation of the hydraulic **actuation** system based on the current position of the crankshaft. The main variables of the engine and the hydraulic system are presented in the work but the simulation is able to give information of a wider set of variables (volumetric flow, flow velocity, valve velocity, etc.). Moreover, the effects of changes on the dimension of component of the hydraulic actuation system or parameters of the IC engine can be analyzed by means of the simulation.

Future work on the topic can be to include the thermodynamic behavior in the combustion chamber for its analysis. Also, the use of closed-loop control strategies dedicated to obtain an improved performance and efficiency of the engine can be studied by means of the proposed simulation. Cylinder de-activation schemes can be simulated to improve the fuel consumption when the engine is working on different conditions, [Corno et al., 2019], [Strange and Chen, 2020].

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Biography

Andrés M. Sada-Regalado is a researcher, and in-thesis student of Automotive Design Engineering in Universidad de Monterrey, Nuevo León, México. His research focuses on multi-system simulation, internal combustion engine's technology, finite element analysis and structural and multi-physics simulation. He is currently working on structural analysis using the FEM to optimize the design of various heavy duty machines and products. He is constantly looking for new opportunities to gain new experience for personal and professional development and also researching to learn about technologies in the automotive industry, from OEMs to Tier companies. Always looking for future development in projects by the hand of colleges and researchers.

David F. Novella-Rodriguez has been an associate professor in the engineering department at Universidad de Monterrey UDEM, since 2019, working in the automotive design engineering group. He received a Ph.D. in communications and electronics from the Instituto Politécnico Nacional, Mexico in 2015. He studied a M.Sc. in microelectronics and an engineering degree in automatic control. He worked from 2017 to 2019 as a post-doctoral fellow in the Université Grenoble Alpes in the linear systems and robustness team at GIPSA Lab in Grenoble, France. His research interests include the modeling and control of systems with time-delay, control systems for ventilation of underground mines, and the modeling of fluid flow networks. Currently, he is a member of the National Researchers System of Mexico Level I.

Juan C. Tudon-Martínez obtained the PhD degree in sciences with a major in Mechatronics in 2014 from Tecnológico de Monterrey. From 2015, he has been an associate professor at the School of Engineering and Technologies in Universidad de Monterrey. Prof. Tudon-Martinez is a member of the National System of Researches, level 1. He has leaded several consulting projects in Mexico, related to the modeling and process control. Prof. TudonMartinez has published more than 65 research papers indexed in Scopus and/or JCR databases. His research is mainly focused on modeling and process control, vehicle dynamics, vehicle control, and fault diagnosis and fault tolerant control in vehicles.