DYNAMICAL SIMULATION OF A VALVETRAIN MECHANISM: AN ENGINEERING EDUCATION APPROACH

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Abstract. *The present work aims to present a valvetrain model considering the dynamics functioning aspects of Otto's engine. Model will be constructed using Adams/View that is a powerful modeling and simulating environment that allows building, simulating, refiinge, and ultimately optimizing any mechanical system. In fact, the model will help engineering students to understand what it happens in terms of displacement, velocity and acceleration of the valve versus time, the force in the spring versus time, and also, the torque in the cam. Relative to spring force, during the Otto engine cycle, the cam lobe must be able to open and close the valve as far, as fast and as smoothly as possible. The closing force for the valves is applied by the valve spring, which is also responsible for maintaining contact between the cam lobe and the valve. Dynamic forces impose limits on cam and valve lift. Thus, the simulation model allows determining these forces and displacements through the cam rotation. As major results the authors wish to make available a model which is capable to show in 3D the animation of a valvetrain mechanism of an Otto engine, detaching the main curves for analysis and evaluation of the mechanism performance.*

Keywords*: Valvetrain Mechanism, Engine Simulation, Adams/View.*

1. INTRODUCTION

The petrol or oil engine, which is the source of power with which the society are immediately concerned, is a form of internal combustion 'heat engine', the function of which is to convert potential heat energy contained in the fuel into mechanical work.

The dawn of the motor vehicle age occurred around 1769 when the french military engineer, Nicholas Joseph Cugnot (1725-1804), built a three-wheeled, steam-driven vehicle for the purpose of pulling artillery pieces In 1784 a steam-powered vehicle was built by the Scottish engineer, James Watt (1736-1819), which proved unworkable. By 1802, Richard Trevithick (1771-1833), an Englishman, developed a steam coach that traveled from Cornwall to London. (Gillespie, 1992).

The first engine to come into general use was built by Lenoir in 1860. The engine resembled a single-cylinder, double-acting horizontal steam engine, with two power strokes per revolution. The next significant step was the Otto and Langen atmospheric or free-piston engine of 1866; the fuel consumption was about half that of the Lenoir engine. The main features of the engine were a long vertical cylinder, a heavy piston and a racked piston rod (Stone, 1999).

At the same time commercial exploitation of oil wells in the USA was occurring, as a result of the pioneer drilling by Drake in 1859. This led to the availability of liquid fuels that were much more convenient to use than gaseous fuels. Liquid fuels without doubt accelerated the development of internal combustion engines. In 1876 the Otto silent engine using the four-stroke cycle was patented and produced. As well as being much quieter than the free-piston engine, the silent engine was about three times as efficient. Immediately following the Otto silent engine, two-stroke engines were developed. Patents by Robson in 1877 and 1879 and Clerk in 1878 and 1881 describe the two-stroke cycle under different functioning conditions (Stone, 1999).

The first practical automobiles powered by gasoline engines arrived in 1886 with credit generally going to Karl Benz (1844-1929) and Gottlieb Daimler (1834-1900), Otto and Langen's partner (Gillespie, 1992). Over the next decade, automotive vehicles were developed by many other pioneers with familiar names such as Rene Panhard, Emile Levassor, Armand Peugeot, Frank and Charles Duryea, Henry Ford and Ransom Olds. In Europe the familiar companies like Daimler, Opel, Renault, Benz and Peugeot were becoming recognized as automotive manufacturers.

Thus accordingly to history one type of internal combustion engine is the spark ignition engines, also called Otto engine, where the fuel is ignited by a spark. Another possible type is the compression ignition engines, where the rise in temperature and pressure during compression is sufficient to cause spontaneous ignition of the fuel.

During each crankshaft revolution there are two strokes of the piston, and both types of engine can be designed to operate in either four or two strokes of the piston.

The four stroke operating cycle can be defined as: induction, compression, expansion and exhaust strokes. Each stroke refers to the movement of the piston. In the induction stroke, the inlet valve is open, the air enters and fuel is usually pre-mixed with the air. In the compression stroke valves are closed and piston travels up the cylinder. As it approaches to top dead centre, ignition occurs. In the expansion, combustion propagates throughout the charge, raising the pressure and temperature, and forcing the piston down. At the end of the power stroke the exhaust valve opens, and irreversible expansion of the exhaust gases is termed. In the last phase, the exhaust valve remains open to expel gases.

Depending on the engine architecture, it has a valve set that allows induction and exhaust, cams, camshafts operating via cam follower, push rods and rocker arm. This mechanism is known as valvetrain and is responsible for the internal combustion engine functioning (Heisler, 2008).

This way, the present work aims to present this mechanism involving a valve-operating system with overhead poppet valves (OHV – overhead valves), where the camshaft is either mounted in the cylinder block. The proposed model is simple and it will allow engineering students understanding dynamics aspects of this mechanism. Model will be constructed using Adams/View (MSC Software) that is a powerful modeling and simulating environment that allows building and simulating any mechanical system. In fact, the model permits the analysis of displacement, velocity and acceleration of the valve versus time, the force in the spring versus time, and also, the torque in the cam.

2. VALVETRAIN MECHANISM

Since the origination of the automobile, the internal combustion engine has evolved considerably, but one aspect has remained throughout engine development. The camshaft has been the primary means of controlling the valve actuation and timing. The valvetrain mechanism, in its simplest form, consists on a camshaft via cam followers, springs, valves and mechanical linkage (push rod and rocker arms) (Bosch, 2007 and Stone, 1999). During the mechanism functioning, as the camshaft rotates, cam lobes, attached to the camshaft, interface with engine's valves. This interface may take place via mechanical linkage and the result is, as the cam rotates it forces the valve to open. The spring return closes the valve when the cam is no longer supplying the opening force (Brader, 2001).

Since the timing of the engine is dependent on the shape of the cam lobes and the rotational velocity of the camshaft, engineers must make decisions early in the automobile development process that affect the engine's performance Taraza *et al.* (1999) and Brader (2001). This fact points to the importance of understand the dynamic functioning and design influence of such a mechanism.

Basically, there are four valve-timing concepts as shown in Fig.1. According to the design, the drive system, which opens the valves, has four different configurations. Figure 1 represents a push-rod assembly, where the camshaft is placed laterally to the cylinder head. In this mechanism, a bucket moving back and forth in the cylinder head absorbs the cam lobe's lateral force, while transferring its linear actuating pressure to the valve stem. Others designs refer to OHC and DOHC, but in this work, it will be simulated an OHV design (push-rod assembly) (Bosch, 2007).

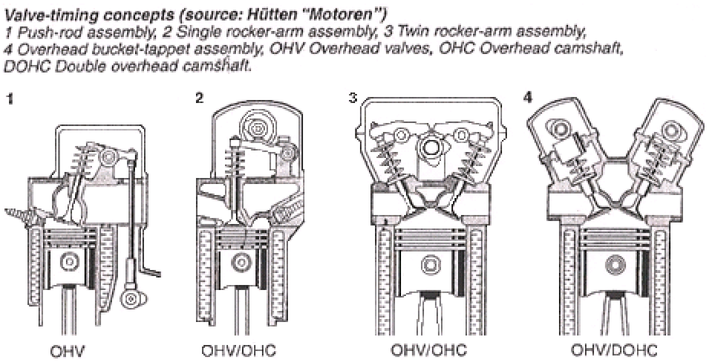


Figure 1 – Valvetrain Models (Source: Bosch, 2007).

Taraza *et al*. (1999) mentioned that a push-rod assembly is largely employed in diesel engines. Although to reduce the number of gears necessary to put into motion the camshaft, this kind of construction add mass in the construction linkage; hence it can cause high vibrations and, consequently, high levels of noise. Figure 2 highlights this mechanism.

The most commonly used valve in valvetrains is the mushroom-shaped poppet valve. It has the advantage of being cheap, with good flow properties, good seating, easy greasing and good heat transfer to the cylinder head as mentioned by Stone (1999) and Heisler (2008). The rocker arm in a push rod assembly supports the push rod in one side and the spring/valve in the other one, as shown in Fig.3. Its function is to transmit the push rod movement to allow valve opening. In the center, the rocker arm has a hole to incase itself in the set axle. Figure 4 shows rocker arm mounted in the engine.

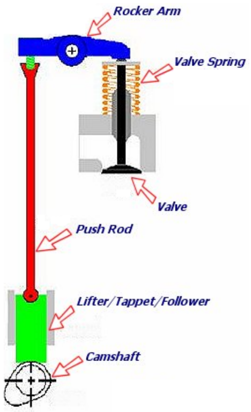


Figure 2 – Push-rod.

The valve's spring has the length and the stress adapted according to the engine. In fact, the spring retains the valve in order to keep air entrance close, whenever the rocker arm is not pressuring the set.

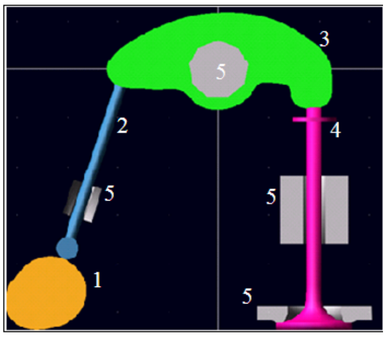
Figure 3 – Rocker arm.

Figure 4 – Rocker arm mounted in the motor.

3. PROPOSED METHODOLOGY APPLIED IN THE MODEL DEVELOPMENT

In this section, the authors present the main actions to construct a simple model capable to simulate the valvetrain mechanism.

The geometrical dimensions were obtained from an original and real system from a common vehicle. Precision metrological equipments were used in this step, like caliper, micrometer, etc. From the measured geometrical data, and due to the model be a simple mechanism, it was design directly in the Adams/View software. In Fig. 5 is shown the designed model and in the table beside it is shown the part names and the software tool used to build each one. As it just said it represents an OHV engine design (Fig. 2).



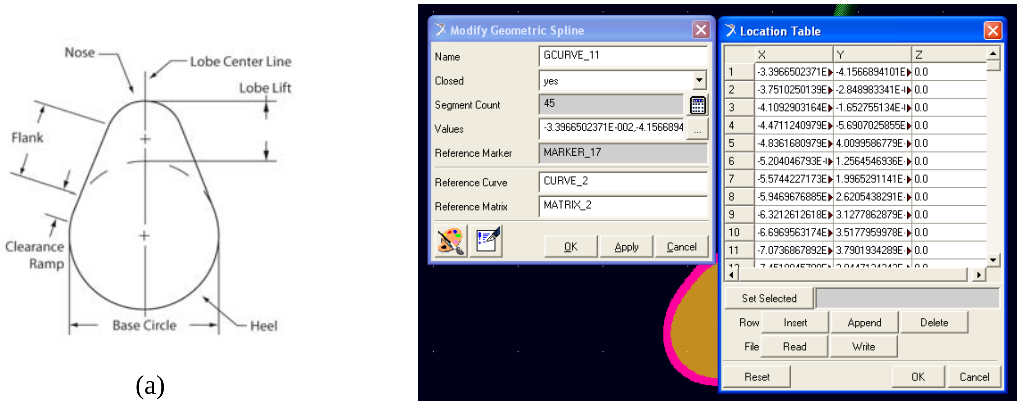
Part	Name	Tool
1	Came	Spline
2	Rod	Cilinder
3	Rocker	Spline
4	Valve	Revolution
5	Supports	Revolution/circle

Figure 5 – Multibody model developed in Adams/View software.

As seen in the table of the Fig. 5, some parts of the model require the manipulation of specific tools, like *spline*, *cilinder* and *revolution*, which are no trivial tools.

The *spline* was used for the construction of the rocker and cam. This tool requires previous information of some points which compose the surface formed by it. The part (cam or rocker) is created selecting these points, and the software is capable to interpolate them creating the complete surface. Following, it is presented the cam design. The same process is used to design the rocker part.

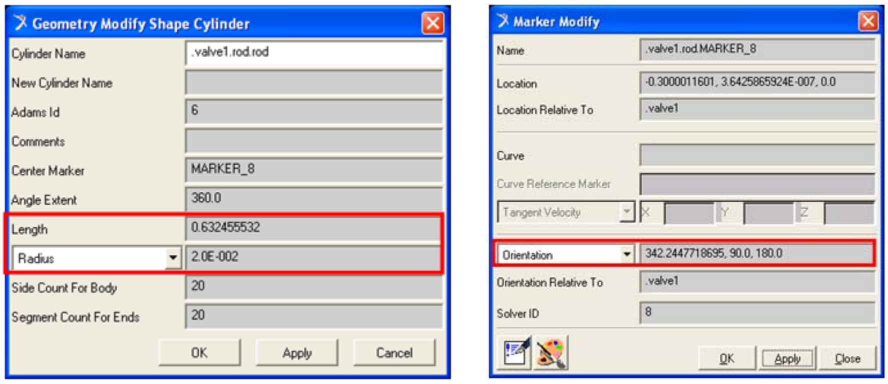
The cam model used in this work is shown in Fig. 6.a. The length from the nose to circle center is 0.08 m. The radius of the base circle is 0.035 m and the lobe lift is 0.03 m. The Figire 6.b illustrates the *spline* toolbox used to insert the points necessary to design the cam surface.



(a) (b)

Figure 6 – a) Cam; b) *Spline* toolbox

The cylinder tool was used to build the rod as shown in Fig. 5. For use this tool is necessary to know the radius and the length of the cylinder. In this model, the length is 0.19 m and the radius is 0.01 m. The toolboxes used to design this part are shown in Fig. 7. Figure 7.a shows the toolbox used to define the cylinder geometry and Figure 7.b shows the toolbox used to inform the orientation of the rod (inclination), as seen in Fig. 5. The inclination modification is done changing the orientation of the center marker (this is a kind of local referential of the part) of the cylinder (namely MARKER_8 as shown in Fig. 7.a).



(a) (b)

Figure 7 – a) Cylinder geometry; b) Rod orientation (inclination).

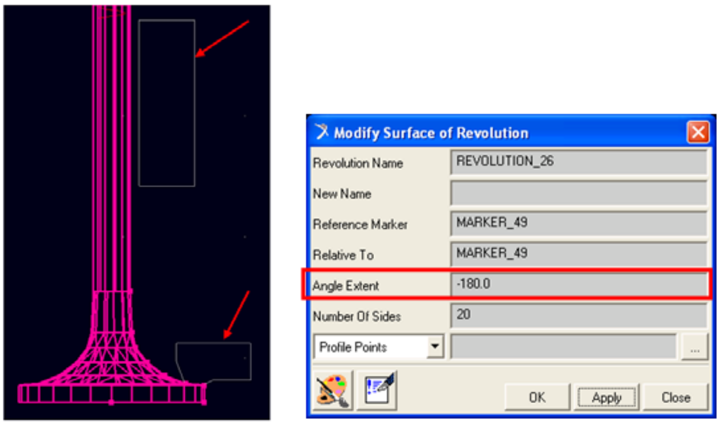
The revolution tool was used to design the valve part and its supports, including those of the valvetrain mechanism. Before use this tool it is necessary design a "generator" of each part of interest, using the *polyline* tool. So, the revolution tool rotates each one around a defined axis. In Fig. 8.a is shown two "generators" which is the support for the valve (gray lines). To obtain these parts like they are shown in Fig. 5 (cross section) it is necessary to define the angle extent as 180°, as seen in Fig. 8.b.

After design the geometrical parts of the model, it is necessary to define the joints of the mechanism, which will define the movement limits of the system. In this model were inserted seven joints: two revolute joints, one translational joint and four primitive joint.

The revolute joints are used to define rotation (center axis of the cam and rocker). In the revolute joint inserted in the cam part, it was imposed a constant angular velocity of 6.28 rad/s, which is described in the software like the expression: *360d*time*. The translational joint was inserted in the valve, which restricts the up and down movement of this part.

The primitive joints were defined in the rod (two) and in the rocker (two). These joints establish the link of these two parts and the connection of the rocker and valve.

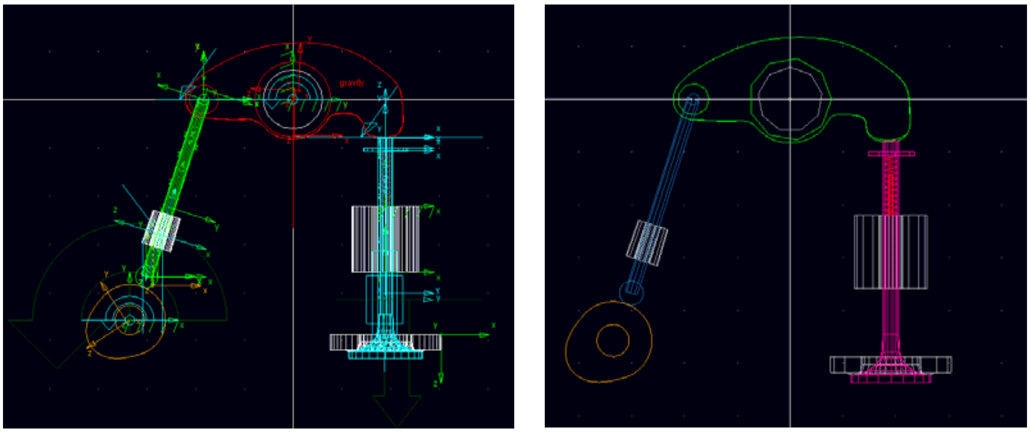
In the valve part was necessary to create a spring damper mechanism. The spring attached to the valve guarantees its return to the initial position, allowing the valve closure. So, it is necessary to add a pre-load in this system (spring /damper) to ensure a correct dynamic simulation. This step approximates the virtual model to the real model and eliminates noises in the simulated results. The imposed pre-load was 100 lbf (445 N).



(a) (b)

Figure 8 – a) “Generators” used to design the valve supports; b) Angle extent of the supports.

The completed model is illustrated in Fig. 9.



(a) (b)

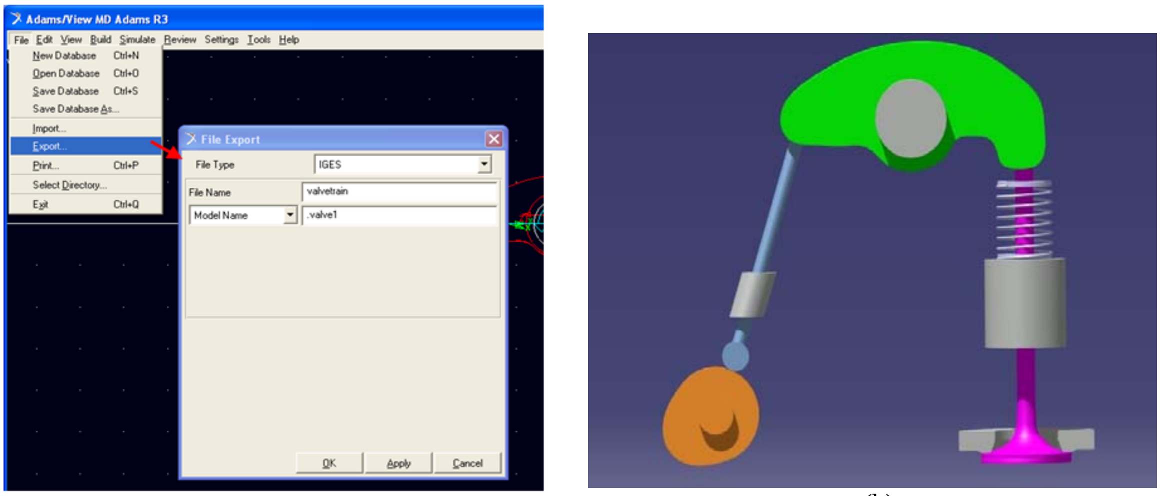
Figure 9 – a) Complete model with all items visible; b) Complete model with only the parts visible.

After the mechanism completely designed, the next step is the dynamic simulation. In this stage is possible to obtain important results in the study of this type of mechanism. For didactic application, the computational results obtained from the virtual model can be compared with theoretical results. It is possible too to show the motion of the system, and to modify the dynamic of the model varying the mean parameters of the mechanism. All this is possible in real time.

The simulation was performed from the toolbox “interactive simulation controls”, which is located in the Main Toolbox of the Adams/View. Figure 10 shows the used simulation parameters: *End Time* = 5.0 s and *Steps* = 500.

Figure 10 – Simulation parameters

If desired, the geometrical model designed can be exported to CAD (Computer Aided Design) software in order to obtain a better appearance of the system. In this work the software used was the CATIA® V6 which is a multi-platform CAD/CAM/CAE developed by the company *Dassault Systémes*. The export operation is shown in the Fig. 11.a. Figure 11.b shows the model in the CATIA interface.



(a) (b)

Figure 11 – a) Export operation; b) Model in the software CATIA.

4. RESULTS

This section presents the main results obtained with the kinematics model simulation. It is important to note that these results are basic for this kind of mechanism. In general, the literature in this field presents these results to the student.

Figure 12 illustrates the torque measured in cam's rotation axis and the translational displacement of the centroid of the valve. These results are important to designers, because they can evaluate cam's behavior according to an established displacement.

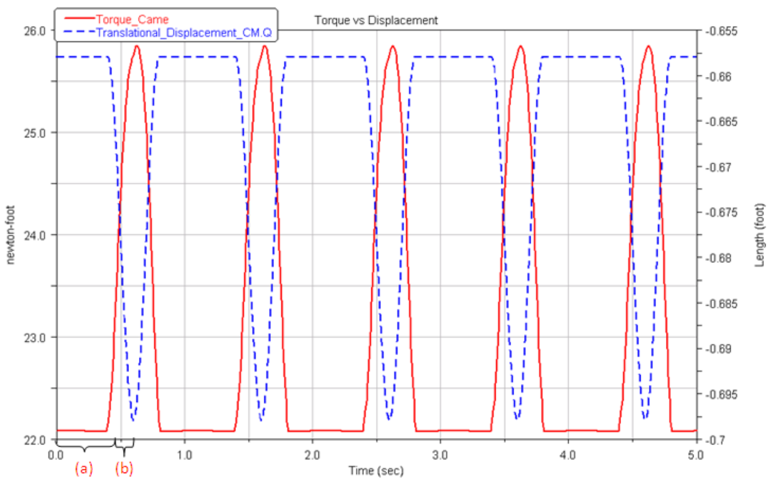


Figure 12 – Torque and Displacement measured in the cam.

In Fig.12, between 0s and 0.39s (a), the torque's curve covers the base circle of the cam (Fig.6.a). During this time, an amount of torque is required to extrapolate the contact force between the cam and the rod, its value is constant and near to contact force's value. At the same time, the valve's displacement is null, because any movement is transmitted by the cam to the rest of the system.

Between 0.4s and 0.63s (b), the cam turns and now it covers the flank zone until its nose (Fig.6.a), at this point the cam has the great radius. In the graphic, torque's curve rapidly goes up, since the torque directly depends on the radius. The torque, at this time, moves the valve opening it until its maximum point, allowing the fuel intake. It can be noticed a difference in time about 0.03s between the point of maximum torque and the point of maximum displacement of the valve; it points that the valve displacement is direct linked to the maximum torque.

Forces obtained at this time are important to an engine designer, because based on these results he can determine the required power to set in motion the system. This way, a sensitivity analysis can be carried out considering changes in the rocker arm dimensions. This kind of analysis allows determining suitable dimensions in order to save energy and reducing cam's torque. When the torque goes down quickly, it means that cam returns to the base circle (Fig.6.a) and the valve closes. This movement repeats regularly during the engine functioning.

In Fig.13, the velocity and acceleration of the valvetrain's centroid is shown. The relation between both shows that, when the valve has a maximum or minimum velocity, the corresponding acceleration, in the same time, is zero, for example, at 0.5s and 1.5s (yellow circles). The curves are periodic, and velocity and acceleration are positive when the valve suffers a deceleration according to the used reference axis -y.

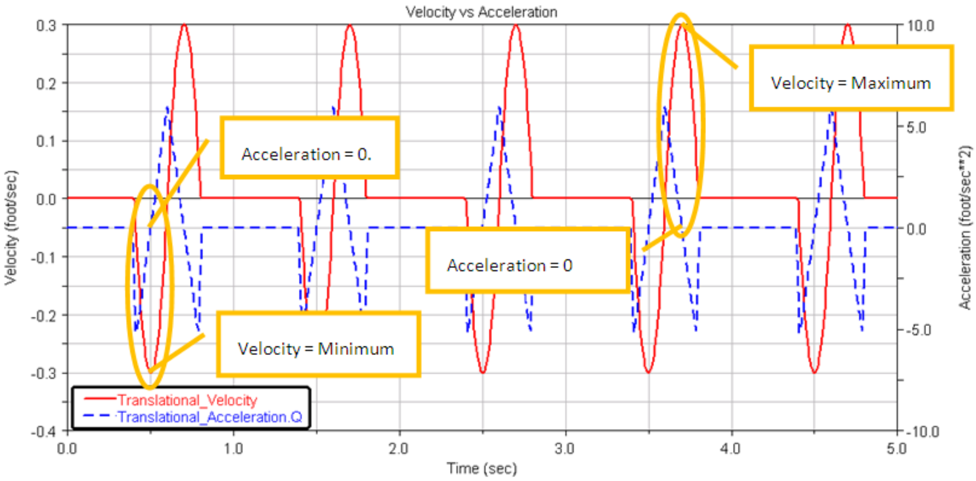
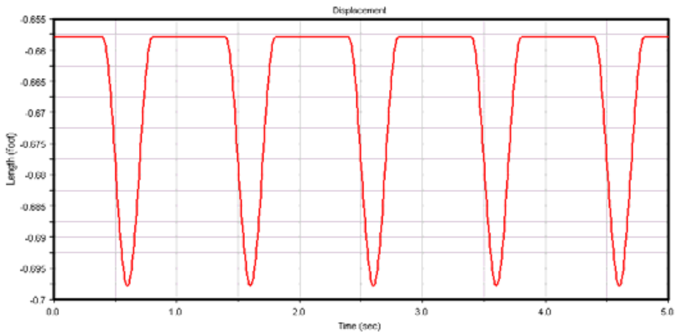
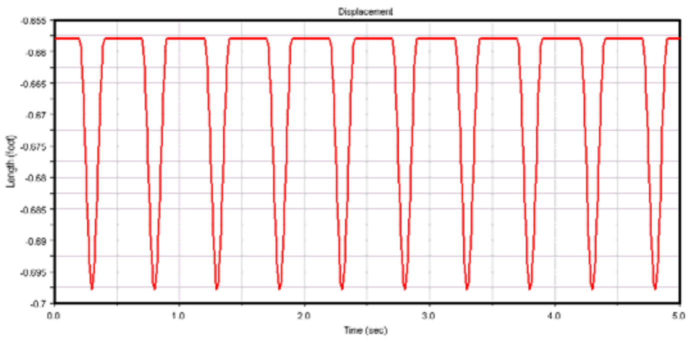


Figure 13 – Velocity and acceleration of the valve's CM.

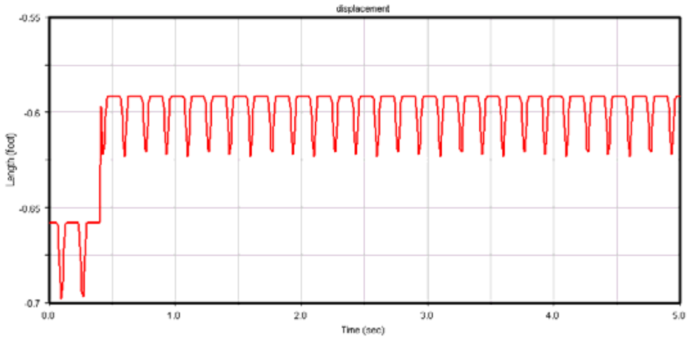
The next simulations refer to a sensitivity analysis in terms of the angular speed imposed to the system, which is constant during the simulation period, like described in section 3. For these analyses, the velocity was gradually increased (steps of 6.28 rad/s), from 6.28 rad/s until 37.29 rad/s. The value of 37.29 rad/s is the angular velocity that corresponds to the proper functioning of the mechanism. Figure 14 shows de results obtained: Fig. 14-a corresponds to the angular velocity 6.28 rad/s, Fig. 15-b correspond to the next increment of the velocity (12.56 rad/s), and Fig. 15-c is the last velocity, 37.29 rad/s.



(a)



(b)



(c)
Figure 14 – Displacement of the valve.

Analyzing the Fig. 14, it is possible to note that the system's resonant frequency was overcome, in other words, the system do not respond correctly from a certain speed, and the results became unsatisfactory. This fact occurs because the spring response time is different of the mechanism operation time. After sensitivity analysis, it is easy to conclude that the maximum velocity without damage to the mechanism is 26.18 rad/s.

Another important feature of the software Adams is the Adams/Postprocessor module, which permits the user creates videos of the simulations. Figure 15 illustrates this feature in Windows® environment.

Figure 15 – Simulation movie.

This movie presented in Fig. 15 is a great teaching tool because it is possible to analyze the simulation results (graphs) together with the dynamic of the system. One can watch simultaneously the movements of the mechanism with the graphs results. This tool is able to increase the understanding of the operating system, improving the understanding of the graphs results and still arouses interest of the student for learning.

5. CONCLUSIONS

This work presents a valvetrain model considering its dynamics and kinematics functioning aspects of Otto's engine. This is a classic mechanism used in automotive and mechanic engineering courses. The model of this mechanism was constructed using the multibody software Adams, specifically Adams/View and Adams/Postprocessor modules.

It was shown that this technological tool can help the engineering students to better understand what it happens in terms of displacement, velocity and acceleration of the valve versus time, the force in the spring versus time, and also, the torque in the cam, which are all basic results obtained from this mechanism.

The Adams/View has been proved to be a very suitable tool for teaching this mechanism for students and can be extending to others mechanism. All the simulation results obtained agree with the theory, like illustrated at the classical literature. The complementary tool, the Adams/Postprocessor is effective for the presentation of results including movies.

Therefore, with the union of these two tools (Adams/View and Adams/Postprocessor) an interesting methodology for teaching the kinematic of mechanisms was presented. If the student wishes, new simulations can be performed in real time in the classroom, just by changing parameters of simulations and geometrical parameters, which can be done easily. In this article the focus is not to teach students to use the software but use this tool (the software and their modulus), which is commonly used only in research of specific mechanisms, as a technological aid to stimulate the learning in classrooms and laboratories.

6. ACKNOWLEDGEMENTS

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