Simulation Models for a Cam in a Diesel, Multiple Unit's Engine Valvetrain

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Abstract: Rail vehicles with an independent traction system are still used for both passenger and freight railway transport. In the case of passenger railway transport, multiple units are spread due to their compact design and favorable running properties. Multiple units of independent traction are powered by a diesel engine. Despite stricter demands on the environmental impact of this type of power, diesel engines will not be replaced by different ones soon. Research in this field is focused on possibilities to improve their efficiency during operation. It is often performed by means of computer modeling, which is an inseparable part of the activities of workers in technical practice as well as in scientific research institutions. The presented research is aimed at studying the characteristics of a cam, which is a part of a diesel engine valvetrain, by means of simulation models. The engine is mounted in a commercially manufactured multiple unit. A simulation model of a valvetrain is created. Further, mathematical descriptions of evaluated cam characteristics are included. The results are depicted in the form of graphical outputs for the chosen initial data. Using designed calculations, it is possible to choose the most suitable parameters, to minimize the dynamic load on the key components of an engine.

Keywords: diesel multiple unit; valvetrain; cam characteristics, simulation models

1 Introduction

Railway transport of goods and passengers is already an inseparable part of the transport system in developed countries, as well as in developing countries. The advantages of railway transport play an important role in why it is chosen above other forms of transport. The relatively acceptable environmental impacts resulting from the operation of rail vehicles are one of the main advantages of rail transport [1] [2]. The efforts to still reduce fuel consumption, noise, vibrations and other force scientists, designers and engineers to develop new technical solutions. This is reflected in the new designs of freight wagons [3-5], passenger wagons and multiple units [6].

Transport of passengers by railways is ensured by passenger wagons. Recently, multiple units have become more and more popular. Regarding the multiple unit design, they include several individual vehicles (wagons), and their design is similar to that of trams. While trams are used for local and shorter distances in cities and towns, and they are designed for lower running speeds, lower transport capacity and lower powers [7], multiple units are able to transport a large number of passengers at high running speeds and the operate between towns and cities several tens to hundreds of kilometers away [8] [9].

Despite the broad electrification of railways, there are still some regions and areas where only multiple units with independent traction can run. These multiple units are usually powered by a diesel combustion engine in combination with a traction device. Although, as described in the next section, new alternative ways [10-13] for rail vehicles with independent traction are being developed [14-16], diesel combustion engines fueled by fossil fuels are still produced and operated. This fact is also detailed in the work [17]. The presented research is focused on the evaluation of the characteristics of a valvetrain cam of a diesel engine applied in a multiple unit, which is shown in Figure 1.

Figure 1
An illustration of the multiple unit

It is necessary to know the essentials of the valvetrain installed in a combustion engine. As it is known, a piston combustion engine is a periodically working machine, in which, heat from fuel is released directly into a cylinder. After the end of a working cycle (expansion), it is necessary to exhaust gas and to fill a cylinder with fresh air. This is ensured by a valvetrain of a combustion engine.

A valvetrain must provide the near perfect emptying and filling of a cylinder, as well as the compression space of a combustion engine. This process must take place in exactly defined moments in time relating to a piston position (valve timing). The valve train of modern combustion engines allows even variable valve timing, which adjusts valve timing to engine rotates and the engine load [18-20]. A valve train has to have high reliability, minimal noise and it has to require minimal operational maintenance [21] [22]. Important parameters are characteristics of the valvetrain cam, which are the main object of this research. It is a part of a more complex project focused on finding ways to improve the operational properties of the multiple units.

2 Literature Review

It is possible to discover that many research works and studies, related to rail vehicles, have been and are still being performed. This reflects the complexity of a rail vehicle and its importance in the field of transport. The goal of these studies is to improve the running properties of rail vehicles from many points of view. The research team of this presented study is focused mainly on the investigation of the dynamic properties of vehicles as well as the improvement of their reliability and efficiency. For these purposes, they employ modern tools of simulation analysis, which allow them to reveal the possibilities of modifications [23]. D. Barta was a member of the research team that made efforts to reduce gas exhaust emissions, who also worked in the research [24] [25]. Here, the research team performed simulations to evaluate the resulting air pollution due to various types of fuel mixtures. However, it does not include an evaluation of valvetrain cam characteristics. A problem with alternative fuels for diesel engines, which could also be used as a source of power for rail vehicles, is studied by Rayapureddy et al. in the research [26]. They found that diesel engines are fueled by a mixture of biocomponents, which helps to reduce harmful gas emissions. This also shows new horizons for diesel engines. Despite complex research, they have not focused on valvetrain characteristics. The issue of the maintenance of the locomotive traction engine is investigated in the study by Zvolenský et al. [27]. The main goal of the presented work is to improve the situation with frequent failures, which can happen during a modernized locomotive operation. An analysis of the valvetrain of a traction engine is also missing there. The research by Balabayev et al. [28] investigated the possibility of isolating and managing exhaust gases from diesel locomotive engines to reduce environmental impact and enhance operational safety. The research is performed through experiments. In addition to an experimental stand, it includes a mathematical model for this issue. However, a model of the valvetrain of an engine, is neither created nor developed. The research team of the Wabtec Corporation company summarized, in the scientific work [29], a technical development of a performance improvement of the diesel engine of its design. It is proposed, that the engine be applied as a source of power for a locomotive, i.e., for a rail vehicle. The research is performed through experiments, which include the optimization of intake valve closure. However, neither the dynamics of a valvetrain nor its characteristics are presented. There is presented a study by Jiang et al. [30]. It reflects the current efforts to reduce air pollution by exhaust emissions. For this purpose, the research team established a simulation model which corresponds to the

16V265H diesel engine. It is the engine that serves to traction a diesel-electric 6-axle locomotive. They present possibilities to diminish unwanted gas emissions by biodiesel. Despite the research being focused on the analysis of the powertrain of a locomotive engine, a model for dynamic analysis of the valvetrain of the engine is not included. The scholars of the same workplace, also led by Jiang [31], addressed the optimization analysis of a locomotive diesel engine intake system using the software Matlab-Simulink and GT-Power. This research is again focused on the minimization of environmental pollution, by the combustion of alternative fuels. In this study, dynamic analysis is not performed. The scientific work [32] includes a proposal for a method that can indicate faults in the valvetrain of a diesel engine. Although the method can be applied to more types of diesel engines, it is not proposed, especially for locomotive diesel engines, and it does not include any simulation model with dynamic analysis of valvetrain characteristics. Current efforts to apply a hydrogen fuel cell and a battery as a source of power for a locomotive are investigated in a study by Cole et al. [33]. The work applies the dynamic simulation of the powertrain properties. However, it is not primarily focused on the valvetrain dynamics and characteristics. Moreover, it is aimed at heavy haul freight locomotives, not on a passenger rail vehicle. Nguyen and Pham worked on research [34], where they developed a computational model based on the finite element method in order to analyze the thermal and mechanical loads occurring in a diesel combustion engine. This is a complex study, and it provides an overview of the results of an investigated phenomenon that appears during the combustion of fuels in the engine. However, the research is not mainly focused on valvetrain cams and their characteristics.

As it can be concluded, based on an overview of the current research, a relatively significant emphasis is placed on the efficiency of rail vehicle powertrains in terms of fuel consumption, exhaust emissions and the load of components of a traction engine. Therefore, it is possible to analyze some of the parameters of a diesel combustion engine for a rail vehicle.

3 Simulations and Calculations of Selected Parameters of a Valvetrain

A valvetrain is a mechanical system that can oscillate under certain conditions in such a manner that it can interrupt contact between individual components, or an oscillating valve can jump off its seat due to the valve's high speed. Extreme oscillation can lead to broken valve springs, resulting in severe damage to an engine. These problems occur the most often when the excitation frequency is near to some eigenfrequency (danger of resonance). To reach the high volume power of engines, some parameters and quantities are increased, which results in the higher load of a valvetrain. Engine speed is one of them, furthering the fullness of a lifting curve and the pressure in a cylinder. Higher engine speed and fullness of a lifting curve led to higher accelerations of valvetrain components together with higher amplitudes of higher harmonic excitation frequencies from a cam. A similar effect is caused by the pressure of exhaust gas in a combustion space at the beginning of the opening of an exhaust valve. These factors result in increasing the forces acting in a valvetrain and increasing the amplitudes of oscillation of valvetrain components, mainly a valve. This reduces the lifetime of an entire valvetrain.

In practice, it is necessary for a designer to continuously verify its behavior and properties, depending on various parameters just in the state of design by means of a corresponding mathematical model (a system of equations of motion and other defining equations). The accuracy of the results strongly depends on a fact: how a used model corresponds to reality.

A dynamic model with two degrees of freedom, is used, for simple calculations of the valvetrain dynamics. For more accurate calculations, much more complicated models, with higher degrees of freedom are employed. These complex models are usually set-up in multibody software.

3.1. Dynamical Models of a Valvetrain

Calculation models are used to analyze valvetrain characteristics. The choice of a model depends on the required accuracy of the results. The quality of a model determines the number of degrees of freedom of a chosen dynamical model. Further, whether a valve clearance or damping is considered, the variance of the exhaust gas force is also considered. Examples of dynamical models of a valvetrain for the calculation of dynamical characteristics are shown in Figure 2a. The parameters in Figure 2a are as follows: m_1 – mass of a part of a camshaft, m_2 – mass of a rocker arm, m_3 – mass of a spring, m_4 – mass of a valve, I_1 – moment of inertia of a part of a camshaft, I_2 – moment of inertia of a rocker arm, φ_2 – angular deflection of a rocker arm, x_4 – a lifting of a valve, k_3 – stiffness of a spring, b_3 – damping in a valvetrain, F_2 – a spring return force.

Figure 2b depicts a model with one degree of freedom. The stiffness of an entire valvetrain is represented by a spring with a stiffness k_r, a valve spring is k_{rv}, and it is reduced to a valve. From an oscillation point of view, the valvetrain mass is critical; therefore, eigenfrequency depends on a ratio of stiffness and mass (eq. 1).

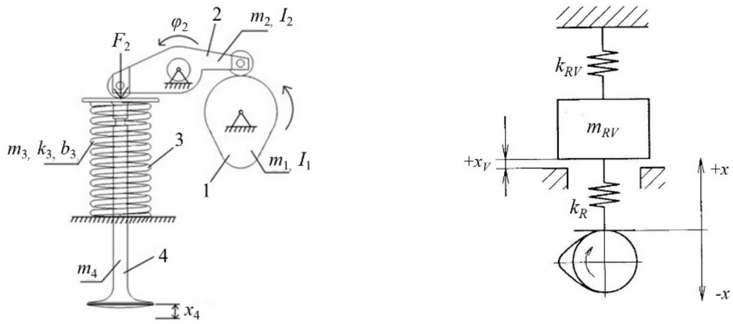
After simplification, an approximate eigenfrequency of a valvetrain is given by Eqs. (1-2):

$$\Omega = \sqrt{\frac{k_r + k_{rv}}{m_{rv}}} \tag{1}$$

or

$$f = \frac{\Omega}{2 \cdot \pi} = \frac{1}{2 \cdot \pi} \sqrt{\frac{k_r + k_{rv}}{m_{rv}}} \tag{2}$$

where m_{rv} is the valvetrain mass reduced to the valve.



(a) (b)

Figure 2

Examples of dynamical models of a valve train: a) a scheme of the OHC valve train, b) a simplified dynamical model of a valve train with one degree of freedom

The derivation of quantities written above, comes from the procedure described below.

The kinematic energy of the valvetrain (Figure 2b) is given by Eq. (3):

$$E_k = \frac{m_o \cdot \dot{x}_v^2}{2} + \frac{J \cdot \omega_v^2}{2} + \frac{m_1 \cdot \dot{x}^2}{2} \tag{3}$$

where m_o is the valve mass, $\dot{x}_v$ is valve velocity, J is the moment of inertia of a rocker arm regarding its axis of rotation, ω_v is the angular velocity of a rocker arm, m_1 is the mass of other components, and $\dot{x}$ is a cam lifting velocity.

When a reduction to the valve is applied, then k_{rv} is stiffness reduced to a valve, m_{rv} is the valve train mass reduced to the valve, k_r is the total stiffness of valve train components, x_v is a valve lift, and x is reduced lift of a cam.

Mass reduced to the valve can be determined as follows (see Eq. (4)):

$$E_k = \frac{m_{rv} \cdot \dot{x}_v^2}{2} \quad \Rightarrow \quad m_{rv} = \frac{2 \cdot E_k}{\dot{x}_v^2} \tag{4}$$

When the flexibility of the valvetrain is neglected, potential energy is given by pressing the valve spring. When the valvetrain mechanism includes two valve springs, it is necessary to determine their total characteristic, and then it is used in calculations. Potential energy is given by Eq. (5):

$$E_p = \frac{1}{2} \cdot k_{RV} \cdot (x_v + x)^2 + \frac{1}{2} \cdot k_R \cdot (x + x_o)^2 \quad (5)$$

where k_v is the valve spring stiffness, k_z is the equivalent stiffens of the other components, x is the lift, x_{vo} is the valve spring pressing due to preload, and x_o is the additional spring pressing due to preload.

A reduction to the valve leads to the potential energy expressed by means of stiffness reduced to the valve as follows (see Eq. (6)):

$$E_p = \frac{1}{2} \cdot k_{rv} \cdot (x_v + x_{vo})^2 \quad (6)$$

By comparing Eqs. (4) and (5), the stiffness reduced to the valve can be obtained (see Eq. (7)):

$$k_{rv} = k_v + k_z \cdot \left(\frac{x + x_o}{x_v + x_{vo}}\right)^2 \quad (7)$$

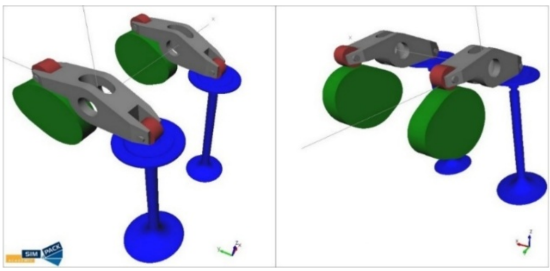


Figure 3
An MBS model of the OHC valvetrain

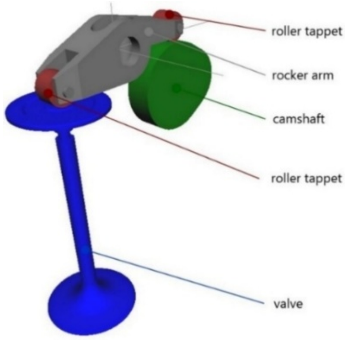


Figure 4
Individual components of the created OHC valvetrain

A multibody model of a valvetrain was created using the commercial software Simpack. It is depicted in Figure 3 and Figure 4. It is a multibody software that has wide applications in modeling the dynamical system of any kind, similar to other commercially used software working on the multibody system principle [35]. Designers and engineers use it mainly in automotive, railway and aerospace engineering and, in principle, it can be used practically for setting-up a mechanical system of any machine. It is possible to investigate the impact of rail vehicles running, on the ride comfort for passengers [36] [37], the structure of individual vehicle components, as well as the impact on the railway track [38-42].

4 Results and Discussion

It is possible to perform simulation computations based on the created model of a valvetrain. In this section, the results of calculations of trigonometrical lifting characteristics of cam movements are presented.

The trigonometrical lifting characteristics of a cam has a following form (see Eq. (8)):

$$x'' = A_0 + A_1 \cdot sin(a \cdot \varphi) + A_2 \cdot cos(b \cdot \varphi) \tag{8}$$

where x'' is the acceleration of a cam, A_0, A_1, A_2, a and b are constants, and φ is an angle of cam rotation.

It is possible to create both symmetrical and asymmetrical acceleration diagrams by means of sinusoidal and cosinusoidal curves for low rotational speeds ($\delta_d < 10^{-4}$). The parameter δ_d is the dynamical factor, calculated as follows (see Eq. (9)):

$$\delta_d = \left(\frac{m_e}{k_e}\right) \cdot \Omega^2 = \left(\frac{\Omega}{\omega}\right)^2 \tag{9}$$

where m_e is the equivalent mass of the system, k_e is the equivalent stiffness of the system, ω is the angle velocity of a cam, and Ω is the eigenfrequency of a cam.

It is assumed that the total increasing output and back movement x_0 is located on a middle angle of a cam $\varphi = \beta_0$. An acceleration curve can be divided into j segments. Angles β_1, β_2, β_3, ... corresponds to these segments, that $\beta_1 + \beta_2 + \beta_3 + ... = \beta_0$. A sum of partial segments x_1, x_2, x_3, ... equals to the total lift or to total back decreasing x_0, i.e. $x_1 + x_2 + x_3 + ... = x_0$

If a middle angle φ/β is assigned to a segment, the value of the ratio φ/β will be zero at the beginning, and it will equal 1 at the end of each segment.

Individual segments of an acceleration curve can be written by means of Eq. (10):

$$x'' = C \cdot sin\frac{n \cdot \pi \cdot \varphi}{\beta} \quad (10)$$

where n = 0.5, 1, 2, or:

$$x'' = C \cdot cos\frac{\pi \cdot \varphi}{2 \cdot \beta} \quad (11)$$

where C is the maximal or minimal value of acceleration in an individual segment, neighboring segments have to have a continuous transition and the same values in the point of connections.

The complex lifting movement of a cam can be described by means of the set of equations for lift, velocity and acceleration as follows (see Eqs. (12-14)):

$$x = x_0 \cdot \left[\frac{\varphi}{\beta_0} - \frac{1}{2 \cdot \pi} \cdot sin\left(\frac{2 \cdot \pi \cdot \varphi}{\beta_0}\right)\right] \quad (12)$$

$$x' = \frac{x_0}{\beta_0} \cdot \left[1 - cos\left(\frac{2 \cdot \pi \cdot \varphi}{\beta_0}\right)\right] \quad (13)$$

$$x'' = \frac{2 \cdot \pi \cdot x_0}{\beta_0^2} \cdot sin\left(\frac{2 \cdot \pi \cdot \varphi}{\beta_0}\right) \quad (14)$$

where x_0 is the maximal deflection (lift), φ is an angle of rotation, and β_0 is the total angle of a segment.

The acceleration diagram of a cycloid cam is calculated using a simulation model. The graphical outputs were created with the help of the Matlab software [43] [44]. There are calculated lift, velocities and acceleration depending on an angle of cam rotation. Graphs in Figures 5 to 7 show waveforms of lift x [mm] (Figure 5), velocity x' [mm/rad] (Figure 6) and acceleration x'' [mm/rad^2] (Figure 7) for a cycloid cam for initial values $\beta_0 = \pi$ rad and x_0 = 15 mm, 20 mm and 25 mm of a sinusoidal cam, where x_0 is the maximal cam lift. Figure 8 depicts the accelerations of the sinusoidal cam with the included dynamical effects.

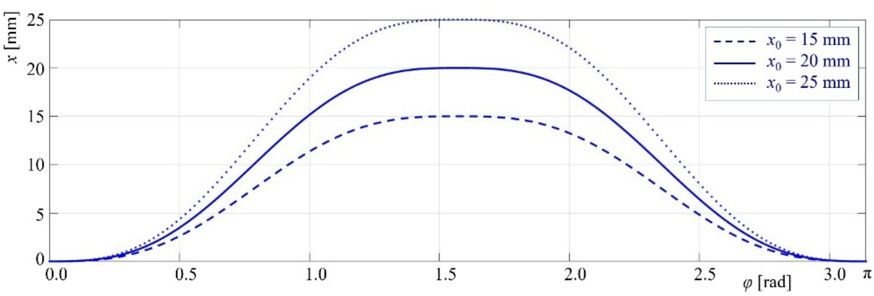


Figure 5
Lift a cycloid cam x for different maximal cam lift x_0

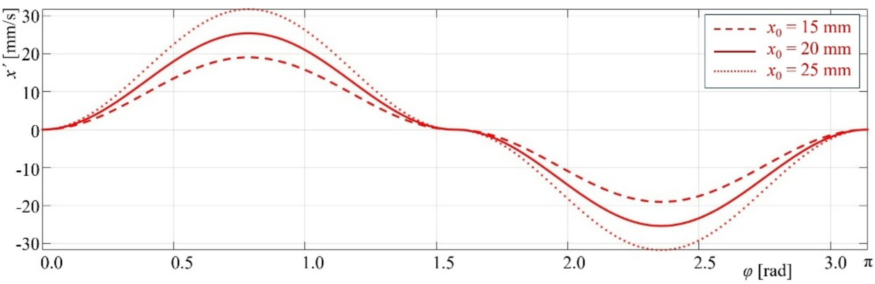


Figure 6

Lifting velocity of a cycloid cam x' for different maximal cam lift x_0

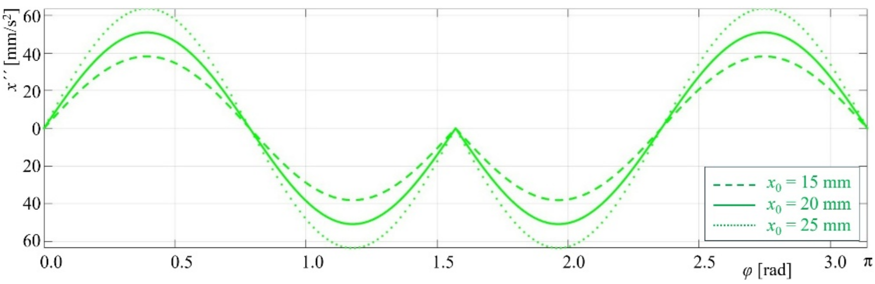


Figure 7

Lifting acceleration of a cycloid cam x'' for different maximal cam lift x_0

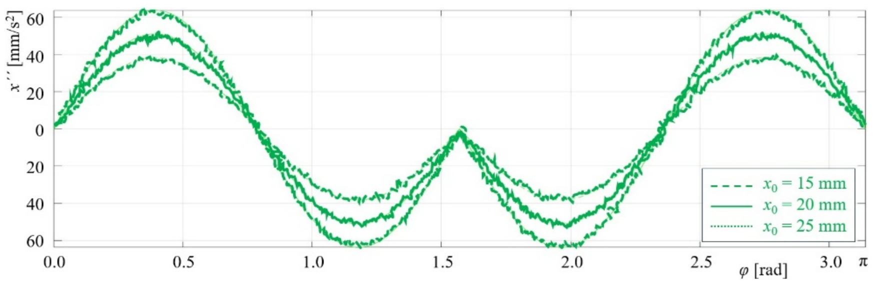


Figure 8

Lifting acceleration of a cycloid cam x'' for different maximal cam lift x_0 considering dynamic effects

As can be seen, the cam lifts from 0 to the maximal values of 15 mm, 20 mm and 25 mm. The maximal values of cam lift are reached for the angle of rotation of π/2 rad. Further, it can be recognized that the cam angular velocity also begins at the value of 0 mm/rad, and the maximal value is at the position π/4 rad and 3/4·π. At the moment of the maximal lift of the cam, the velocity equals zero, which corresponds to the movement principle of the analyzed system. Then, the waveform of angular velocity is similar to the previous segment with opposite values. Acceleration of the cam has the maximal value for the angle of 1/8·π rad and odd multiples. Then, the value of acceleration decreases, and it reaches the zero value for an angle of 2/8·π rad even multiplies. It can be seen that the zero value is reached for the other three positions, namely for π rad, π/2 rad and at the end of the movement.

This trigonometrical acceleration diagram can be improved so that the maximal values of acceleration of the cam will be lower. This would positively influence the dynamic properties of the cam mechanism, lowering the inertia forces.

The improvement is reached when the sinusoidal segments are combined with the segments of constant acceleration. The resulting diagram is called a modified trapezoidal acceleration diagram.

The modified acceleration diagram of a trapezoidal cam consists of six segments, which are symmetrical to each other.

The first half of the diagram has three segments. The first segment is expressed by means of Eqs. (15-17):

$$x = \frac{x'_0}{2 \cdot \pi} \cdot \left[\left(\frac{4 \cdot \pi \cdot \varphi}{\beta_0} \right) - sin \left(\frac{4 \cdot \pi \cdot \varphi}{\beta_0} \right) \right] \tag{15}$$

$$x' = \frac{2 \cdot x'_0}{\beta_0} \cdot \left[1 - cos \left(\frac{4 \cdot \pi \cdot \varphi}{\beta_0} \right) \right] \tag{16}$$

$$x'' = \left(\frac{8 \cdot \pi \cdot x'_0}{\beta_0^2} \right) \cdot sin \left(\frac{4 \cdot \pi \cdot \varphi}{\beta_0} \right) \tag{17}$$

Further, the second segment is described by means of Eqs. (18-20):

$$x = x'_0 \cdot \left[-\frac{1}{2 \cdot \pi} + \frac{2 \cdot \varphi}{\beta_0} + 4 \cdot \pi \cdot \left(\frac{\varphi}{\beta_0} - \frac{1}{8} \right) \right] \tag{18}$$

$$x' = \frac{x'_0}{\beta_0} \cdot \left[2 + 8 \cdot \pi \cdot \left(\frac{\varphi}{\beta_0} - \frac{1}{8} \right) \right] \tag{19}$$

$$x'' = \left(\frac{8 \cdot \pi \cdot x'_0}{\beta_0^2} \right) \tag{20}$$

Finally, the following mathematical expressions are valid for the third segment:

$$x = x'_0 \cdot \left\{ -\frac{\pi}{2} + 2 \cdot (1 + \pi) \cdot \frac{\varphi}{\beta_0} - \frac{1}{2 \cdot \pi} \cdot sin \left[4 \cdot \pi \cdot \left(\frac{\varphi}{\beta_0} - \frac{2}{8} \right) \right] \right\} \tag{21}$$

$$x' = \frac{2 \cdot x'_0}{\beta_0} \cdot \left\{ 1 + \pi - cos \left(4 \cdot \pi \cdot \left(\frac{\varphi}{\beta_0} - \frac{2}{8} \right) \right) \right\} \tag{22}$$

$$x'' = \left(\frac{8 \cdot \pi \cdot x'_0}{\beta_0^2} \right) \cdot sin \left[4 \cdot \pi \cdot \left(\frac{\varphi}{\beta_0} - \frac{2}{8} \right) \right] \tag{23}$$

Based on the equations written above and the simulation model, the trapezoidal acceleration diagram is created.

The resulting graphical output of the simulation computation is shown in Figs. 9-11. Figure 12 shows the accelerations of the trapezoidal cam for the dynamic effects.

As can be seen, the maximal lift of the cam is the same as in the previous case (Figure 9). It is expected because the lift is not influenced by the modified model.

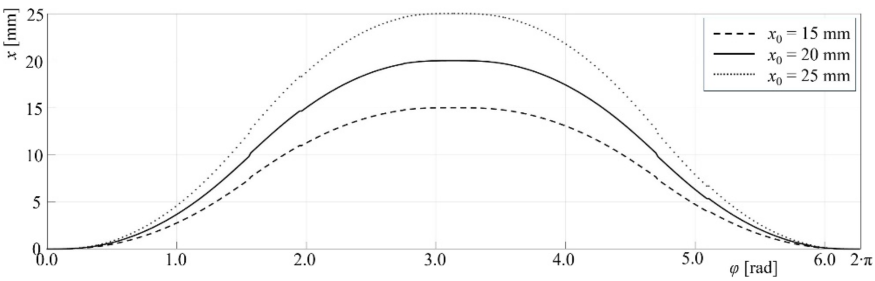


Figure 9

Lift a trapezoidal cam x for different maximal cam lift x_0

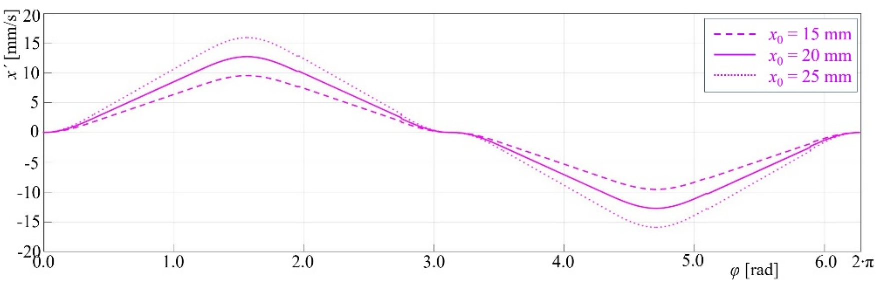


Figure 10

Lifting velocity of a trapezoidal cam x' for different maximal cam lift x_0

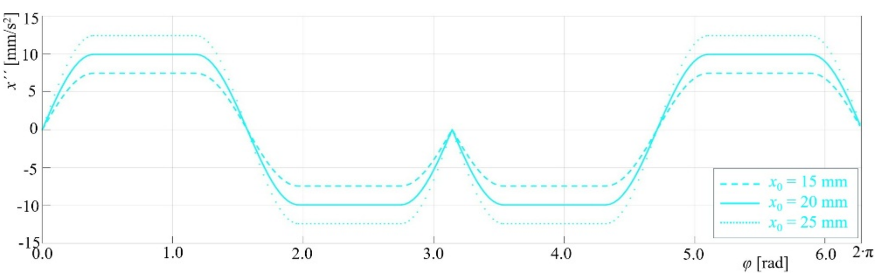


Figure 11

Lifting acceleration of a trapezoidal cam x'' for different maximal cam lift x_0

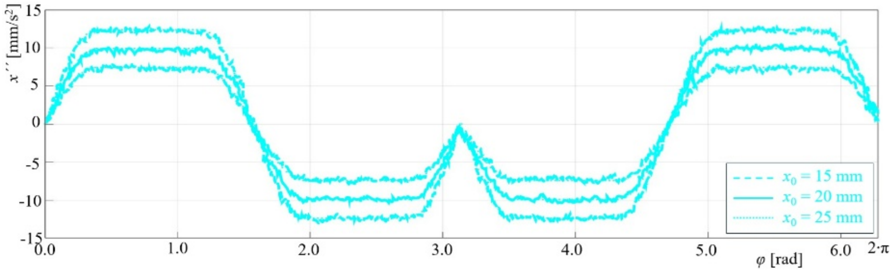


Figure 12
Lifting acceleration of a trapezoidal cam x'' for different maximal cam lift x_0 as dynamic effects

When the angular velocity of the trapezoidal cam and the previous cam are compared, the waveforms are very similar, and only a slight difference is detected. The main advantage of the modification of the model is evident in terms of cam acceleration. As can be seen in Figs 11 and 12, the maximal values of acceleration are decreased in comparison with the previous case. This means that the peak values of the acceleration are eliminated, and their waveform is also changed. The maximal value of acceleration is constant for a certain angle of rotation of the cam, and it is for all four peak values of the accelerations. The zero values of the accelerations for the modified cam (i.e., for the trapezoidal cam) are at the same cam position as in the case of the base model of the cam. There is for the value of 1/2·π rad, π rad, 3/2·π rad and 2·π rad. Based on the findings of simulation computations, the modified trapezoidal cam has smaller values of maximal accelerations at the same initial and input values of the cam system. This is very favorable from the dynamics point of view because it leads to lower values of inertia forces of individual parts of the cam mechanism. Lower values of dynamical forces contribute to lower noise of the system, and longer lifetime of the system; it improves the reliability of the system and the load of the contact areas between key components of the system.

Future research in this field, will be focused on the extension of modeling other important components of the multiple unit drivetrain. The torque transmission from the engine to the drive axle offers a deep analysis and assessment of possibilities for improvement of the system efficiency. The simulation models will be derived and verified, using different computational tools. It is assumed that based on the this research, new ways of improving the drivetrain of the rail vehicle will be found.

Conclusions

The main objective of the study was to investigate the characteristics of the valvetrain in a diesel engine. The valvetrain consists of several components. A cam, is supposed to be a key component of any valvetrain. The presented research includes the development of a model of a valvetrain in commercial multibody software. It is created an OHC valvetrain, which is currently the most used in combustion engines. The created simulation model can be used for the simulation and calculation of various parameters and phenomena that relate to the operation of the valve train.

The presented research mainly focused on the mathematical description of crucial dynamic and geometric properties for components of the OHC valvetrain. A dynamic model of valvetrain was introduced, used in diesel combustion engines and applied as a source of power, for a multiple unit train.

Based on the dynamic models, the exact formulations for the calculation of sinusoidal and trapezoidal cams are presented. The created multibody model of the valvetrain consists of rigid bodies, connected by means of corresponding force elements, mechanical and kinematic joints and other needed couplings.

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