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VARIOUS APPROACHES TO KINEMATIC ANALYSIS IN THE PROCESS OF DESIGN OF PISTON MECHANISMS

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Abstract: The purpose of this paper is to make an analysis of a system of piston mechanism and of its kinematic analysis on the one hand, and modeling and computer-aided design on the other hand. The paper uses kinematic analysis of a mechanism which is made in three methods – analytical, graphic and computer-aided which can also be successfully used in teaching engineers of technical sciences in higher education. Modern computer-aided methods are supported by a special software for analysis of treatment which can simulate not only movement of the mechanism, but it can also determine the position, velocity, acceleration, forces, moments and other parameters in every moment of time; however, control and application of mechanical laws are necessary. Some basic approaches, advantages and disadvantages of presented solutions are described.

Keywords: piston mechanism, kinematic analysis, computer aided solution, piston velocity

INTRODUCTION

A piston mechanism is a kinematic chain which includes three components: crank, connecting rod and crosshead with a slipper whose purpose is to convert straight line motion to rotary motion and vice versa. The use of this mechanism is frequent especially in vehicles with internal combustion engines. A crankshaft, a piston, connecting rod and a cylinder (figures 1, 2 and 3) are parts of piston mechanism. Rotary motion of the crank is transferred to other systems of a vehicle via other parts of the engine, thus ensuring the geometric, kinematic and dynamic accuracy of the vehicle. It is a well known fact that there is a high degree of disturbance of the work of the crankshaft and the connecting rod.

To identify these problems it is necessary to completely examine all parts of the mechanism to avoid high price of repair and maintenance, especially of the cylinder and the piston. The results of some researches show that the cause of damages in these parts lies in the “number of shifts of transmission during a drive, particularly when switching to the lower gear”. [1], [13]

The mechanism has to convert straight line oscillating motion of the piston to a rotary motion of the crankshaft. This enables the work performed

by releasing of heat from the fuel in the piston crown to be transferred as turning moment to the crankshaft. [5], [6]

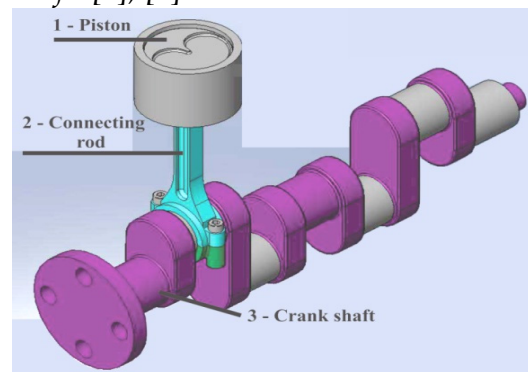


Figure 1. Piston mechanism:
1- piston, 2- connecting rod, 3- crankshaft

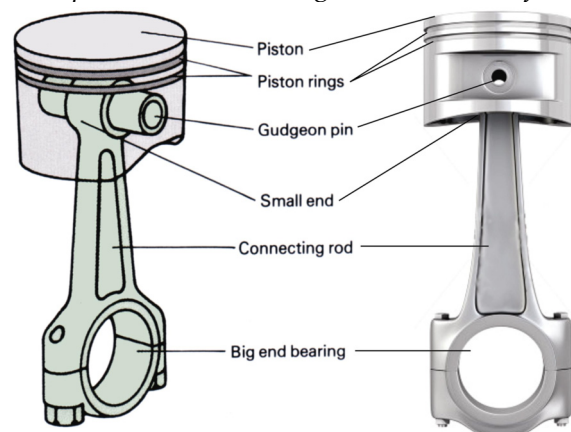


Figure 2. Parts of piston

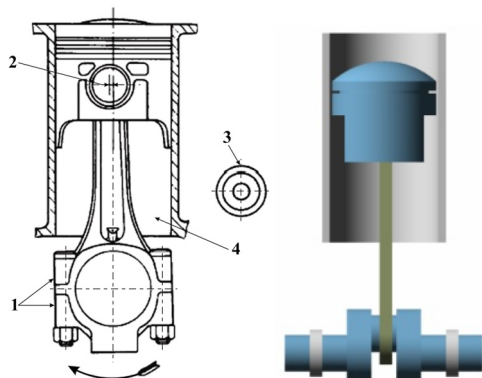


Figure 3. Cylinder of mechanism

The most common mechanisms used are so called simple mechanisms which consist of a piston, a connecting rod and a crankshaft. The complex ones include more elements (crank mechanism with crosshead). [4]

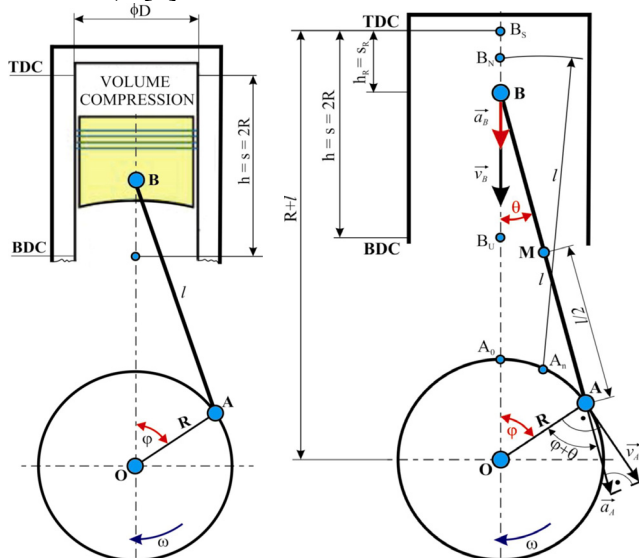


Figure 4. Kinematic scheme of mechanism

The crosshead B produces oscillating straight line motion (Figure 4). The crosshead B is fitted to one end of the connecting rod. It is connected to the piston which moves in a straight line and therefore its motion is also in a straight line. The crank journal A rotates. The position of point A is defined by angle φ which the crank covers with horizontal path of the crosshead (Figure 4). When the point A is in the position ($\varphi = 0$) A_0 ($\varphi = 0$), the crosshead B is in the position B_s (external deadlock). When the point A is in the position that corresponds to the angle $\varphi = 180^\circ$, the crosshead B is in the position B_u (internal deadlock). The crosshead B oscillates between positions B_s and B_u . The distance between B_s and B_u is called the crosshead stroke and is equal to double length of crank $2R$.

KINEMATIC ANALYSIS APPROACHES

The task of kinematic analysis is to determine grafically, analytically or in a computer-aided manner: [5], [6]

1. The position of the crosshead piston of the mechanism for a given position of a driving member or of all driving members (s),
2. The velocity of the crosshead piston of the mechanism (v),
3. Acceleration of the crosshead piston of the mechanism (a) and
4. Kinematic diagrams of piston mechanism (v,s), (a,s), (s,t), (v,t) and (a,t).

The comparison between analytic, graphic and computer-aided solutions of kinematic analysis in this paper was made on the piston mechanism used as a basis to convert rotary motion to a straight line motion in pumps as well as in internal combustion engines in practice. Since the calculations are complex, only determination of the piston velocity will be shown.

Figure 5 shows a mechanism with real behavior in practice (the values of parameters of this mechanism are given only for the case of a specific vehicle movement and are valid only for this movement of the system).

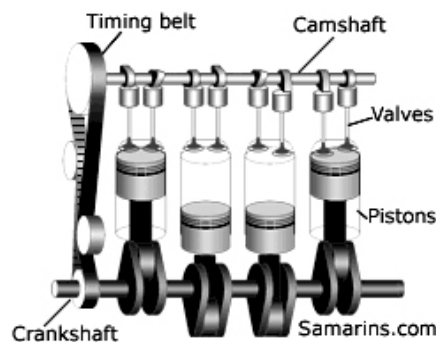


Figure 5. Physical model of mechanism

The simple presentation of real mechanism which serves as a basis for calculation is a kinematic scheme. The kinematic scheme of the mechanism is based on the real mechanism and is shown in figure 4. Individual components of the mechanism in this scheme are given with standard designations to provide simpler calculation. The input values of the given mechanism shown in figures 4 and 5 are: Cylinder diameter $\Phi 80.5$ mm, piston stroke $h = s = 67.4$ mm, number of rotations of the crankshaft at maximal power $n = 6000 \text{ min}^{-1}$, maximal turning moment of the engine $M_{\text{max}} = 106 \text{ Nm}$, number of

turnings of the crankshaft $n = 2900/\text{min}$, radius of the crank $r = h/2$, $r = 67.4/2 = 33.7 \text{ mm}$, radius of piston attaching end $d_1 = 22 \text{ mm}$, radius of the crankshaft attaching end $d_2 = 48.6 \text{ mm}$, radius of the crankshaft $R = 24.3 \text{ mm}$, radius of the piston $D = 80.48 \text{ mm}$, length of the crank $l = 130 \text{ mm}$.

Engineering design and analysis in teaching

Computer technology equipped with suitable software is advantageously used in various branches of practice at present time. [13] Education of mechanical engineers is a process that has to provide knowledge of related natural science, social and technical disciplines, training in using and applying specific methods and development of creativity. CAD (Computer Aided Design) is just one of the methods in design and the software which can be applied in teaching design to encourage development of creative abilities of students. [2], [3]

At the Technical faculty "Mihajlo Pupin" in Zrenjanin the students are taught the said topics in two courses Mechanics and Mechanisms and Computer-aided Design.

The course objective of Mechanics and Mechanisms is to offer the students the basic knowledge in this field. The course is organized in one semester and comprises lectures, practical exercises and calculation exercises. Beside acquisition of necessary theoretical knowledge, it is necessary for the students to learn to solve complex problems of statistics, kinematics and dynamics. At the end of the course the students will be able to use certain theoretical knowledge in designing and calculating and in solving problems related to structure, kinematics and dynamics of certain types of mechanisms. In order to keep pace with development of new technologies, fast and effective learning in as short a time as possible is necessary while at the same time permanent education is a must.

One of the objectives of the course Computer-aided Design is to update the general technical knowledge of the students - future creative professionals: designers and managers, especially in the area of developmental engineering. The objectives also include learning the basic algorithms of new methods in 2D and 3D computer-aided design.

The course Computer-aided Design or CAD/CAM technology includes the following topics: Dimensioning and tolerancing, Machine materials, Design of rotating machine parts, Twisting joints design, Standard profiles and rivets, Axles and springs, Chain and belt drives, Ball and roller bearings, Calculation of shaft and axle load, Gear drives, Mechanisms, etc.

Analytical determination of piston velocity

Velocity projections of two points of rod onto rod direction are equal (figure 6), thus:

$$\overline{Aa'} = \overline{Bb'} \Rightarrow v_A \cdot \cos[90^\circ - (\varphi + \theta)] = v_B \cos \theta \quad [1]$$

Transformation of the previous equation gives:

$$v_A \sin(\varphi + \theta) = v_B \cos \theta, \quad [2]$$

$$v_B = v_A \frac{\sin(\varphi + \theta)}{\cos \theta} \quad [3]$$

To determine the velocity v_B in terms of the angle φ , we use the links:

$$\sin(\varphi + \theta) = \sin \varphi \cos \theta + \cos \varphi \sin \theta,$$

$$\text{tg } \theta = \frac{\sin \theta}{\cos \theta} \approx \sin \theta, \quad [4]$$

because $\cos \theta \approx 1$ is for small angles θ ,

$$\sin \theta = \lambda \sin \varphi, \quad \sin 2\varphi = 2 \sin \varphi \cos \varphi. \quad [5]$$

The final equation for calculation of piston velocity is:

$$v_B = R\omega \left(\sin \varphi \pm \frac{1}{2} \lambda \sin 2\varphi \right) \quad [6]$$

The sign "+" is used for forward stroke and the sign "-" is used for backward stroke.

The velocity v_B equals zero for angles $\varphi = 0$ and $\varphi = 180$, i.e. when the piston is in position B_s and B_u .

The velocity v_B has its greatest value when the direction AB touches the curve of the point A (crank journal).

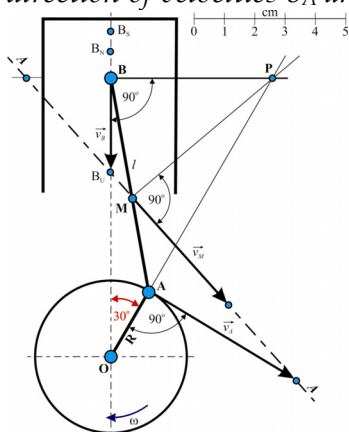
The average velocity of the piston is a very important indication of strength of the assembly piston-ring-cylinder and is calculated according to the term (h - piston stroke, n - velocity of the crankshaft, 1/s): $Y_{\text{sred}} = 2hn$.

Graphic methods for determination of the piston velocity [5], [6]

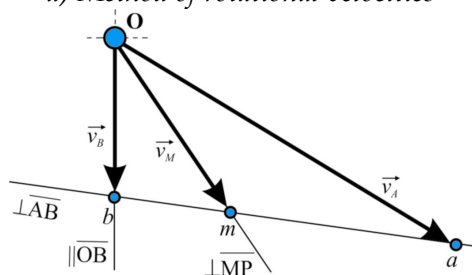
The piston velocity may be determined by graphic means using the method of rotational velocities and the velocity planning method. For both methods it is necessary first to calculate the velocity of crank journal on the basis of values: $v_a = \overline{O'A} \cdot \omega = R \cdot \omega$.

a) Method of rotational velocities

In the method of rotational velocities the given piston mechanism is drawn in proportion U_L (Figure 6-a). In the point A the velocity vector of the point A perpendicular to $\overline{O'A}$, v_A is drawn in a corresponding proportion. The position of momentary pole of velocity P is determined by rotating the direction of velocities v_A and v_B by 90° .



a) Method of rotational velocities



b) Velocity planning method

Figure 6: Graphic methods for determination of crosshead piston velocity

The direction of v_B is horizontal, e.i. it concurs with the direction $\overline{O'B}$, and direction v_A is perpendicular to $\overline{O'A}$. The vector v_A rotates by 90° . From the ultimate point of the rotational velocity v_A , the point A_1 , a parallel line in the direction \overline{AB} is drawn. On the direction \overline{BP} is produced the point B_1 . The line $\overline{BB_1}$ is a graphic representation of rotated velocity v_B . The position v_B is produced by rotating $\overline{BB_1}$ in the opposite direction by 90° . The value of velocity of the point B is: $v_B = U_v \cdot \overline{BB_1}$.

b) Velocity planning method

In this method the given piston mechanism is also drawn in proportion U_L (Figure 6-a). In point A the vector v_A is drawn in proportion U_v . The velocity v_A is parallelly transferred to the point O_1 and drawn in proportion. In the point O_1 the velocity direction v_B is parallelly transferred, in to

the point A_2 (ultimate point v_A) the direction of relative velocity v_B^A is parallelly transferred and is perpendicular to \overline{AB} . A triangle $O_1A_2B_2$ is formed according to the equation: $\overline{v_B} = \overline{v_A} + \overline{v_B^A}$. The line $\overline{O_1B_2}$ in velocity planning (Figure 6-b) graphically represents the velocity v_B whose intensity is: $v_B = U_v \cdot \overline{O_1B_2}$. The velocity slope is made by connecting the ultimate points of the velocity vectors v_A and v_B (Figure 6-a).

Computed-aided design of piston mechanisms

Computer-aided design of mechanisms will be shown on the example of the piston mechanism of the engine, if it is a high-speed engine where the piston motion cycle becomes very short at high rotation speeds of crankshaft (Figure 7). In this case the influence of inertia forces generated during motion dominates in reference to the force generated as a result of fuel mixture expansion in the cylinder. [10]

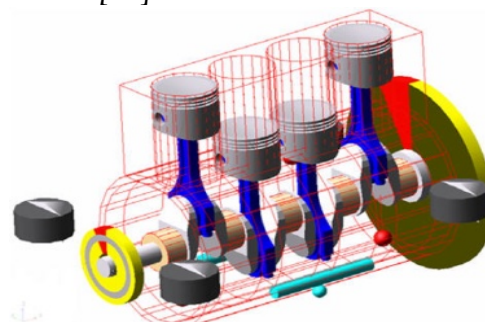


Figure 7. Virtual model of mechanism

A virtual model of the mechanism shown in figure 7 is made using Catia V5 software based on the kinematic scheme (figure 4). The software comprises the simulation of Catia tools suitable for analysis and control of rationalization of complex processes. It helps engineers make kinematic simulations of motions and behavior during the product development process; it enables them to have an insight into the system through a simple definition and animation of links, such as piston and connecting rod, crankshaft, and other. [14] During the modeling process and since it is the software which allows parameter modeling, the necessary links and relations between specific geometric characteristics are made. This enables the preset relations of geometric structure and what is most important, the initial concept of modeling to be retained when some dimensions are subsequently changed, e.g. during optimization.

The necessary limitations in movement of members are inserted, i.e. movable and unmovable members are defined, joints are visualized and thus a kinematic chain of the piston mechanism is formed as a movable assembly which is further used as a virtual prototype in examination and analysis. [9] The view of modeled 3D mechanism is shown in figure 8b. This mechanism model is further used for visual animations.

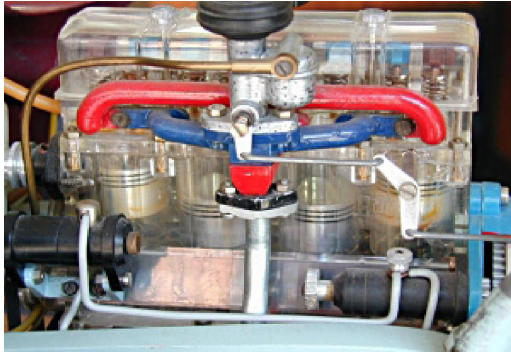


Figure 8. Snapshot of automobile pistons work (simulation)

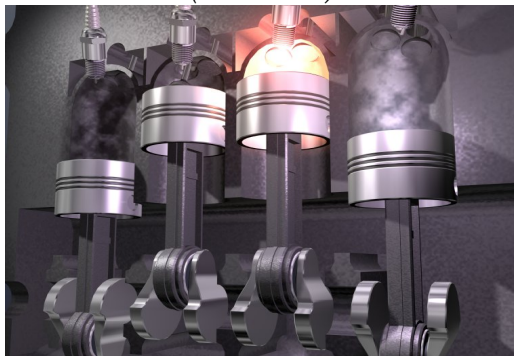


Figure 9. Simulation of the work of automobile pistons
The figures 8 and 9 show the simulation of the automobile pistons work. It helps not only the professionals and engineers in this area, but also drivers to simulate engines and actuators. It is a powerful tool which provides the best mechanism design in industry, enables the best purpose in mechanism of assemblies and subassemblies to be achieved by means of the software. [10]

A VIEW TO THE DESCRIBED KINEMATIC ANALYSIS

The comparison between analytical, graphic and computer-aided kinematic analysis are made on the mechanism which is usually used as a basis for machines and internal combustion engines design in practice. Engineers and mechanical engineering students may easily understand the application and importance of physical behavior of the mechanism model which is analyzed by

calculation, modeling and behavior simulation (based on the real mechanism) [11], [14]

Analytical solution

The advantages of this method include minimal cost for its realization and the possibility to use the table applications for obtaining mathematical function. The disadvantages: mathematical equations terms are long-term; they require an excellent mathematical knowledge of the operator.

Graphical solution

The advantages of this method are: minimal cost for its realization, possibility to use graphical software, relatively quick solution of obtaining output values for one concrete combination of defined input parameters. The disadvantages: every change of input values requires processing, a new graphic solution; inaccuracy of results due to impreciseness.

Computer aided solution

Today, there are interactive and useful 3D software solutions which can be used to model very complex models [7], [8]. The advantages of this method are: visualization of motion mechanism with its details; fast data processing and output; possibility of variable combinations of input values; possibility to use output data for other purposes; direct transfer to dynamic analysis. The disadvantages are: expensive software and hardware, only engineers who are familiar with the work on this equipment may be engaged.

The final decision about which method will be used depends only on the researchers and their abilities. If they are good at mathematics, they will choose analytical and graphic method, but if they use software and hardware, they will choose computer-aided method. In all three cases they must know the basic principles of mechanics (kinematics and dynamics).

CONCLUSIONS

Mechanism design is thought to be one of the most fascinating topics in mechanical engineering. In every modern plant there is a series of automatic operations connected to the production, assembly, transportation of parts, which need the use of mechanisms. The development of robotics and mechatronics is impossible without any knowledge of mechanism design. Therefore mechanism design

is of wider importance for everyday practice as well as for modern technology.

Computer using in designing and constructing is not news any more, but inevitability. Introducing the computer technology in designing and constructing process changes a character of user's work and changes his professional preparation. There are plenty of techniques of governing the application of corresponding program packages for the designing process. Designing with its requests includes needs for simulations of real conditions as well as analysis of interaction of models with the surroundings.

The machine or mechanism design always starts with kinematics consideration. Kinematics is the study of geometry of motion, i.e. of relations between linked parts and their motion in relation to each other. Insufficient knowledge of kinematics may result in a design of a system with failures, with no optimal effect and/or with insufficient reliability. Very powerful personal computers are available today with software products which enable kinematic analysis and synthesis that were not easily, efficiently and cheaply made before. Availability of such complex and expensive computers stimulate defining kinematic principles in design.

It could be said that mechanisms, along with other disciplines, are an area which both a designer and a user of machines must know well. This gives them confidence in solving tasks, designing mechanisms or adjusting them to conditions of use, which will satisfy all necessary requirements. The prerequisite for this is certainly a good knowledge of modern software tools.

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