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Three Views on Kinematic Analysis of Whitworth Mechanism of a Shaping Machine

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***Abstract*— Machines play a very important role in today's industry because they are the foundation of automation. An essential integral part of each machine is the mechanism. In many cases, there are several mechanisms working independently inside the machine or the movements of the individual mechanisms are joined. It is necessary to understand a mechanism ́s motion to be possible to set up its right working conditions and so also to achieve the most appropriate machine efficiency. The article deals with the kinematic analysis of a Whitworth mechanism. This mechanism is a part of a shaping machine that is used in real technical practice. Three approaches (analytical, graphical and solution with computer aid) to the specification of kinematics characteristics of a cutting tool motion are presented in the article. Also, the advantages and disadvantages of the presented approaches are briefly described in the paper. A comparison of results of kinematic analysis has shown that there are no differences in the achieved values; they are only in an accuracy that follows from the essence of individual approaches to the solution.**

***Index Terms*— Whitworth mechanism, shaping machine, kinematic analysis, characteristics**

I. INTRODUCTION

A mechanism can be considered rigid parts that are arranged and connected so that they produce the desired motion of the machine. There is a difference between a machine and a mechanism: All machines transform energy to do work, but only some mechanisms are capable of performing work. The mechanism is usually part of a machine where two or more pieces are combined, so that the motion of the first compels the motion of the others, according to a law depending on the nature of the combination. The operation of any machine depends upon two things: the transmission of certain forces and on the production of determinate motions. In designing, due consideration must be given to both of these, so that each part may be adapted to bear the stresses imposed on it, as well as have the proper motion relative to the other parts of the machine. A structure that supports the moving parts and regulates the path motions, or kind of motion, is called the frame of a machine. In discussing the motions of the moving parts, it is convenient to refer them to the frame. The frame absorbs the forces or moments that originate at the transformation of motions. The components, which actuate mechanism, are drivers, the other components whose motion are caused are called follower. [1-3]

The design of mechanisms has two aspects, analysis and synthesis of mechanisms. The analysis consists of techniques of determining the positions, velocities and accelerations of certain points on the members of mechanisms. The angular positions, velocities and accelerations of the members of mechanisms are also determined during the analysis of mechanisms. By analysis of mechanisms, the trajectory of particular points and the orientation of the members at particular points of time are obtained. If the desired set of positions, velocities and accelerations at definite points of time are stipulated, then the synthesis of mechanisms comprises of mathematically determining the geometry of members of mechanisms such as to produce the desired results. When that mechanism is operated it will pass through the stipulated points with the required velocity and acceleration, and the members will have the desired orientation. Synthesis of mechanisms as per the requirement can be achieved through two ways. First, Rational Synthesis, which consists of standard synthesis techniques developed by designers. Being systematic these techniques can be automated using computer programs. Limitation of rational synthesis technique is that it is applicable only to some specific types of mechanisms. The second technique commonly used by design engineers is Informal Synthesis. This design procedure involves first a guess of dimensions of members of mechanisms and then checking the resultant performance by analysis. The dimensions are modified based on previous performance and adjusted such that to obtain results close to desired. In this way, the process of iterative synthesis and analysis is repeated to obtain acceptable design. [4]

The goal of the investigation was to analyse a Whitworth mechanism of real shaping machine from a kinematic point of view, while three different approaches have been used. The achieved results were compared.

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II. KINEMATIC ANALYSIS OF WHITWORTH MECHANISM

The Whitworth mechanism is also known as the quick return mechanism. It represents a revolving crank slider and produces non-uniform stroke movement with slow forward movement and fast backward movement. This mechanism is used in tools, packaging and transport machinery. In shaping machine, the rotary movement of the drive is converted into the reciprocating movement. It is done by the mechanism contained within the column of the machine. The ram holding the tool makes the reciprocating movement. In a standard shaping machine, metal is cut in the forward cutting stroke, while the return stroke goes idle and no metal is cut during this period. To reduce the full machining time, it is important to reduce the time taken by the return stroke. The shaper mechanism should be so designed that it can allow the ram to move at a slower speed during the forward cutting stroke. The cutting speed depending upon the type of material and machining condition whereas during the return idle return time. This mechanism is known as the quick return mechanism. The reciprocating movement of the ram and the quick return mechanism of the machine.

The goal of the kinematic analysis is to investigate the motion of individual components of mechanism (or their choices points) in dependence on the motion of drivers. To investigate the motion means to determine the dependency of the position, velocity and acceleration of the examined members and important points on the motion of driven members or on the time. A point moving in space describes a line called its path, which may be rectilinear or curvilinear. The motion of a body is determined by the paths of three of its points, not on a straight line. If the motion is in a plane, two points suffice, and if rectilinear, one point suffices to determine the motion. A kinematic analysis can be done in several ways such as analytical, graphical or computer-aided solution. [4]

There are several types of *analytical solution* that is usually concerned with the task of the position. Most often numerical method uses the trigonometric rules and mathematical definitions as are functions, differentiation, equations, etc. The advantages of this method are minimal costs for its realization, the possibility to use the table applications for the value obtaining of mathematical functions. Following disadvantages can be taken into account: the expression of mathematical equations is time-consuming, it demands the excellent mathematical knowledge of the operator, this method doesn ́t solve the collisions of components. [5]

The graphical solution is suitable only for the solving of planar mechanism and comes out from the kinematic scheme of mechanism sketched in the selected scale with the scaled input parameters in vector form. The advantages of this method are the minimal costs for its realization, similarly, as it is at the numerical approach, the possibility to use the graphical software, relative fast solution at the obtaining of output values for one concrete combination of defined input parameters. The disadvantages are: for every change of input value it is necessary to process new graphical solution, inaccuracy, it doesn ́t solve the collisions of components. [6, 7]

A solution with computer aid uses the special software dedicated to that. Today there is very interactive and user-friendly 3D software in the market, which can simulate not only the motion of the mechanism but they can define the position, velocity, acceleration, forces, moments and other parameters in every moment of time in graph or vector version, for example. Inside computer application primarily it is necessary to create the 3D models of individual components of mechanism, secondary to join them by a kinematic linkage which removes a needed number of the degree of freedom. [8] The degree of approximation to the real situation is higher at the difficulty systems as at the simple software, which increases the demands for hardware. Therefore, it is important to correctly choose the simulation tool so as it doesn’t over-price the manufacturing, but so as the achieved results accordingly correspond to the specified conditions on the other hand. This approach expects not only the software control, but it involves the knowledge from the mechanics' field, too. [9,10]

The advantages of this method are: [11]

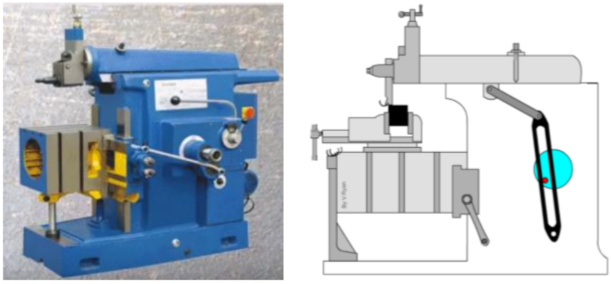
- the visualization of mechanism motion in a virtual environment with its details,
- fast data processing and fast output data acquirement for a variable combination of input values,
- the possibility to use of output data for other applications,
- definition of the material characteristics and a possibility to dynamic characteristics generation,
- the chance for direct transmission to dynamic analysis,
- the ability of components impact determination in virtual background.

The disadvantages are:

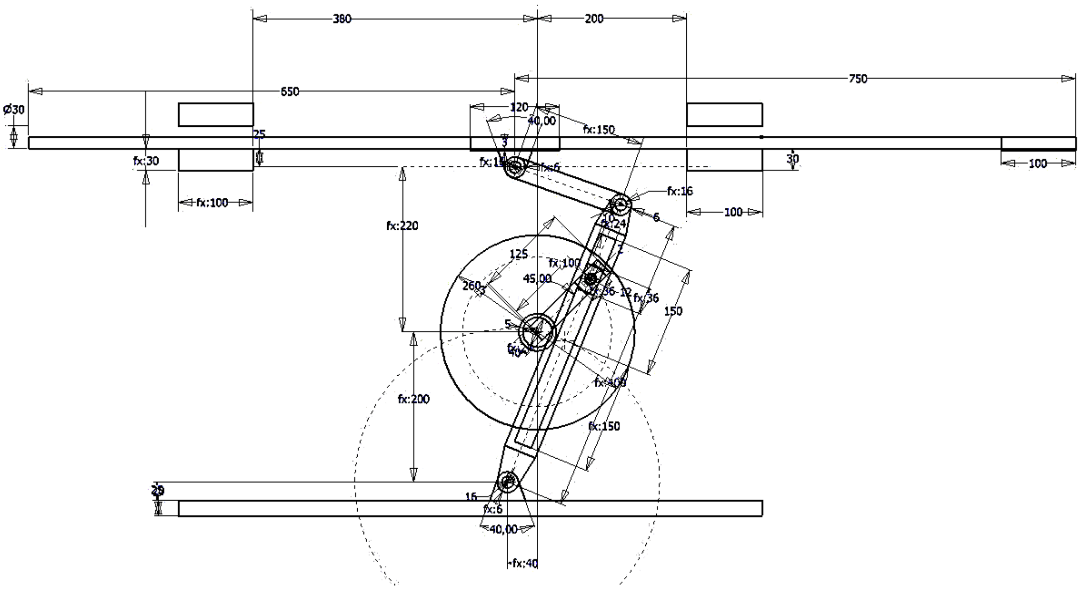
- expensive software and hardware equipment,
- the necessity of electric power,
- the necessity for an operator to know to work with equipment (software, hardware).

The comparison of the analytical, graphical and computer-aided kinematic analyses was realized on the Whitworth mechanism presented in Fig. 1.

This quick return mechanism converts rotary motion into reciprocating motion, but unlike the crank and slider, the forward reciprocating motion is at a different rate than the backward stroke. At the bottom of the drive arm, the peg only has to move through a few degrees to sweep the arm from left to right, but it takes the remainder of the revolution to bring the arm back. This mechanism is most commonly seen as the drive for a shaping or planing machine. [12]



a) b)



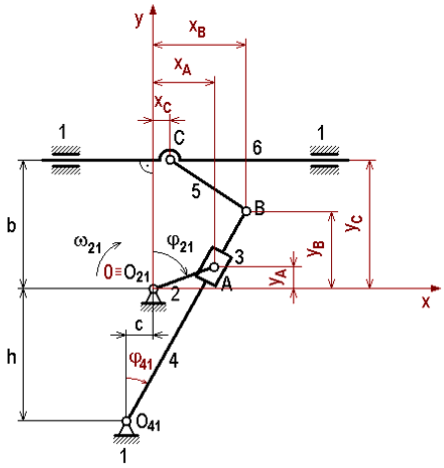
c)

Figure 1. Shaping machine, a) real view, b) schematic view, c) scheme of analysed shaping machine with dimensions

A. Analytical Solution

An analytical method is used when repetitive and extensive analysis of mechanisms is required, as the analytical equations and solutions obtained can be conveniently programmed on a computer. In this approach vector position, velocity and acceleration equations are formulated based on the fact that there are two different paths connecting the points on a vector loop. The equations thus obtained are simplified and programmed using computers. Desirable solutions are obtained by varying the parameters.

The kinematic diagram for an analytical solution was prepared on the basis of real Whitworth mechanism placed in the laboratory at the authors´workplace. It is a reduce scale shaping machine used for the teaching (within mechanics and technology type lessons) and it is shown in Fig. 2.



$$\overline{O_{21}A} = 0{,}1\,\mathrm{m}$$
$$\overline{O_{41}B} = 0{,}4\,\mathrm{m}$$
$$\overline{BC} = 0{,}15\,\mathrm{m}$$
$$h = 0{,}2\,\mathrm{m}$$
$$b = 0{,}22\,\mathrm{m}$$
$$c = 0{,}04\,\mathrm{m}$$
$$\varphi_{21} = 45°$$

Figure 2. Kinematic diagram of the Whitworth mechanism

The individual components of the mechanism are numbered due to the numerical solution limpidity. The frame has number 1, the driver is the crank with number **2** that rotates angular speed ω_{21}. The goal is to define the motion of component **6** which all points describe a line path. A cutting tool is located at the end of bar **6** which is rigidly connected with. For this specific case, the uniform angular speed value is ω_{21}= 5 rads^{-1} of the body 2 has been considered.

The number of degrees of freedom for a planar mechanism is given by equation (1) also known as the Gruebler equation [12]

$$i = 3(n - 1) - 2j_p - j_h, \qquad (1)$$

where n – total number of links in the mechanism, j_p – the number of primary joints (pins or sliding joints) and j_h – the number of higher-order joints (cam or gear joints).

A coordinate system of mechanism for the analytical solution was located into the point O_{21}, position of the important points is described by x a y coordinate.

The dependency of these coordinates on the angle $\varphi_{21(t)}$ has been defined by the trigonometric method. For point B holds

$$x_B = r_2 \sin \varphi_{41} - c = r_2 \sin\left(arctg \frac{c + r_1 \sin \varphi_{21}}{h + r_1 \cos \varphi_{21}}\right) - c \qquad (2)$$

$$y_B = r_2 \cos \varphi_{41} - h = r_2 \cos\left(arctg \frac{c + r_1 \sin \varphi_{21}}{h + r_1 \cos \varphi_{21}}\right) - h \qquad (3)$$

Position of point C that belongs to body 6 follows the equation (4)

$$x_C = x_B - \sqrt{{r_3}^2 - (b - y_B)^2}\,, \qquad (4)$$

So, the final relations (5) and (6) that defined the position of the point C p and that include only known input data are

$$x_C = r_2 \sin\left(\mathrm{arctg}\frac{c + r_1 \sin\varphi_{21}}{\hbar + r_1 \cos\varphi_{21}}\right) - c - \\ - \sqrt{{r_3}^2 - \left[b - r_2 \cos\left(arctg\frac{c + r_1 \sin\varphi_{21}}{\hbar + r_1 \cos\varphi_{21}}\right) + \hbar\right]^2} \tag{5}$$

$$y_C = b = const \tag{6}$$

Angle position of the crank **2** is specified by angle φ_{21} that changed with time. The values for the comparison of both types of solution, numerical and computer-aided, was done for the specific position of crank **2** at $\varphi_{21} = 45$ °.

The velocity of the point C (as well as the velocity of the whole body **6**, so also the velocity of the cutting tool) can be expressed by the relation (7)

$$v_C = \dot{x}_C = \frac{dx_C}{dt}. \tag{7}$$

Because of the position x_C is a complex function, the determination of velocity v_C consists of several tens of computing steps and it requires the basic mathematical skills of an investigator. The final equation for v_C in regard to the frame is:

$$v_C = \omega_{21} r_1 r_2 \left[\frac{\frac{r_1 + \hbar\cos\varphi_{21} + c\sin\varphi_{21}}{(\hbar + r_1\cos\varphi_{21})^2}}{1 + \left(\frac{c + r_1\sin\varphi_{21}}{\hbar + r_1\cos\varphi_{21}}\right)^2}\right]. \\ .\left\{\cos H + + \sin H \frac{b - r_2\cos(\mathrm{arctg}\,K) + \hbar}{\sqrt{{r_3}^2 - [b - r_2\cos(\mathrm{arctg}\,K) + \hbar]^2}}\right\} \tag{8}$$

where $H = \mathrm{arctg}\frac{c + r_1\sin\varphi_{21}}{\hbar + r_1\cos\varphi_{21}}$ and $K = \frac{c + r_1\sin\varphi_{21}}{\hbar + r_1\cos\varphi_{21}}$.

The acceleration of point C is given by the basic kinematics relation (9)

$$a_C = \dot{v}_C = \frac{dv_C}{dt}. \tag{9}$$

The final equation for a_C in regard to the frame is expressed by (10)

$$a_C = \frac{r_1 r_2 {\omega_{21}}^2}{1+K^2}. \\ \left[\left(\frac{(c\cos\varphi_{21} - h\sin\varphi_{21})\cdot(h + r_1\cos\varphi_{21}) + 2r_1\sin\varphi_{21}(r_1 + h\cos\varphi_{21} + c\sin\varphi_{21})}{(h + r_1\cos\phi_{21})^3} - \frac{2KM^2 r_1}{1+K^2}\right). \\ .\left(\cos(\mathrm{arctg}\,K) + \sin(\mathrm{arctg}\,K)\frac{L}{\sqrt{{r_3}^2 - L^2}}\right) + r_1\frac{M^2}{1+K^2}. \\ .\left(-\sin(\mathrm{arctg}\,K) + \cos(\mathrm{arctg}\,K)\frac{L}{\sqrt{{r_3}^2 - L^2}} + r_2{r_3}^2\sin^2(\mathrm{arctg}\,K)\frac{1}{\left(\sqrt{{r_3}^2 - L^2}\right)^3}\right)\right]$$

where $L = b - r_2\cos(\mathrm{arctg}\,K) + \hbar$

and $M = \frac{r_1 + \hbar\cos\varphi_{21} + c\sin\varphi_{21}}{(\hbar + r_1\cos\varphi_{21})^2}$.

After institution of specific value 45 ° to φ_{21} into the equations (3), (4) and (5), the result position, velocity and acceleration of point C (body **6**) are

$x_C = -\ 0.0309$ m;

$v_C = 0.6676\ \mathrm{ms}^{-1}$;

$a_C = -\ 0.1175\ \mathrm{ms}^{-2}$.

A minus sign on acceleration means that at a given moment (in a given position) the tool will slow down.

B. Graphical Solution

The graphical solution consists of an investigation of velocity and acceleration field of important mechanism points. It provides information about kinematic parameters for a specific time moment, which means that it provides the information on the values corresponding to specific immediate mechanism position. [13]

This technique is based on vector polygon laws. Input and investigated parameters are plotted in a form of vectors, which lengths are drawn in needed scale, orientations are given by arrows and directions by directional angle. The achieved output values have to be backwards changed after solution by means of scale.

The graphical method starts with position analysis by simply drawing the linkage mechanism to scale. Then the velocity analysis is performed which requires the angular position of the links to be determined beforehand. If the velocity of one point on a link is known then the velocity of other points can be found using the vector polygons. Similarly, it is necessary to know the angular velocities of links for acceleration analysis. Thus, the sequence for kinematic analysis of mechanisms is – position analysis, then velocity analysis and then acceleration analysis. [14]

Due to the composite motion of mechanism components, it is necessary considered so-called Coriolis acceleration a_{cor}. Coriolis Acceleration (named after the French scientist G. Coriolis), a rotational acceleration, a part of the total acceleration of a point that appears in the so-called composite motion, when the transferred motion, that is, the motion of a moving frame of reference, is not translational. It appears as a consequence of a change in the relative velocity of a point v_{rel} in the transferred motion (motion of the moving frame of reference) and of the transferred velocity in the relative motion. Numerically, the Coriolis acceleration is

$$a_{Cor} = 2\omega_{trans} v_{rel} \sin\alpha, \tag{11}$$

where ω_{trans} is the angular velocity of rotation of the moving frame of reference about some axis and α is the angle between v_{rel} and the axis. [15]

The direction of the Coriolis acceleration can be obtained by projecting the vector vrel on a plane perpendicular to the axis and rotating this projection by 90 ° in the direction of the transferred motion. The Coriolis acceleration is equal to zero when the motion of the moving frame of reference is purely translational or when $\alpha = 0$. [16]

The graphical solution of the mechanism is shown in Fig. 3.

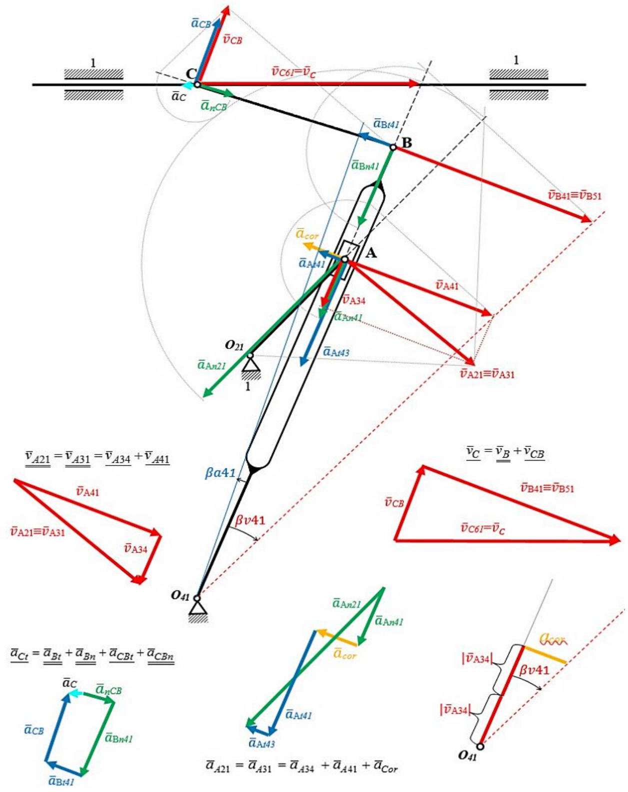


Figure 3. Graphical solution

C. Solution with a Computer Aid

A virtual model of the Whitworth mechanism (Fig. 4) was created in software Autodesk Inventor Professional based on the kinematic diagram. After the preparation of 3D models of individual components, the needed connections were defined, such as pin joints, sliders and others, in order to the motion of the virtual mechanism corresponds with the real mechanism.

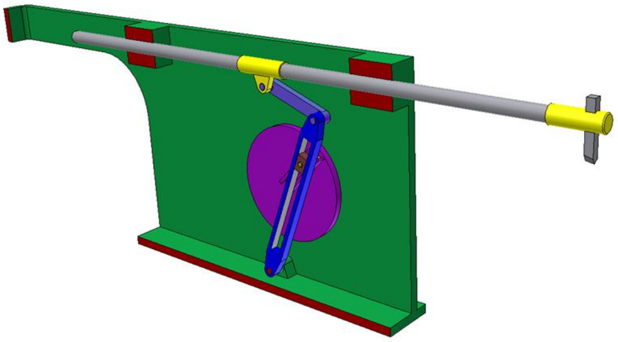
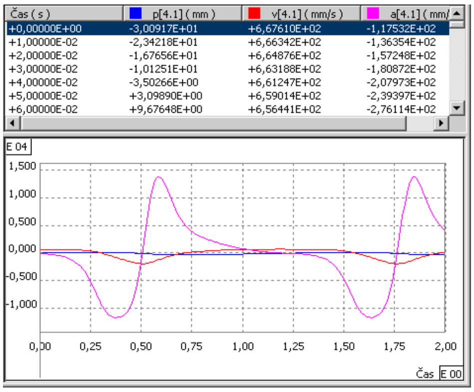


Figure 4. A virtual model of the mechanism

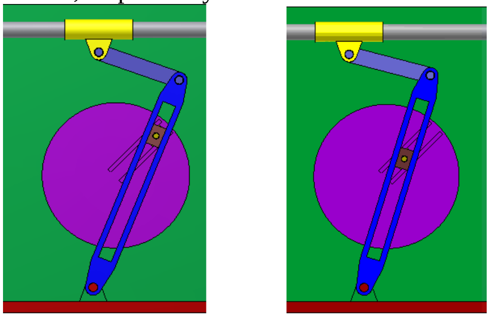
Servo-motor was defined in the driver member of mechanism (crank **2)** and results were observed in point C that also represents the movement of the cutting tool fixed to the rod **6**. Output data are readable directly in the software environment as values or as dependencies or they can be sent to other software (e.g. MS EXCEL) for the next processing. The dependencies of position, velocity, and acceleration of point C on time are presented in Fig. 5.



Čas (s)	🟦 p[4.1] (mm)	🟥 v[4.1] (mm/s)	a[4.1] (mm/
+0,00000E+00	-3,00917E+01	+6,67610E+02	-1,17532E+02
+1,00000E-02	-2,34218E+01	+6,66342E+02	-1,36354E+02
+2,00000E-02	-1,67656E+01	+6,64876E+02	-1,57248E+02
+3,00000E-02	-1,01251E+01	+6,63188E+02	-1,80872E+02
+4,00000E-02	-3,50266E+00	+6,61247E+02	-2,07973E+02
+5,00000E-02	+3,09890E+00	+6,59014E+02	-2,39397E+02
+6,00000E-02	+9,67648E+00	+6,56441E+02	-2,76114E+02

Figure 5. Output data of kinematic analysis

The mechanism was designed in the way to be possible to change the parameter *r* that is a characteristic dimension of the drive component 2. Thus, the output (kinematical characteristics of the cutting tool) can be also optimized so as to be met the requirements for its motion. The drive rod design with a possible change in input "*r*" parameter and comparison of achieved results (dependencies *x(t)*, *v(t)* and *a(t)*) for two various dimensions r_1 = 100 mm and r_2 = 45 mm are shown in Figs. 6 and 7, respectively.



a) r_1 = 100 mm *b)* r_2 = 45 mm

Figure 6. Drive rod design with possible variation in the input dimension

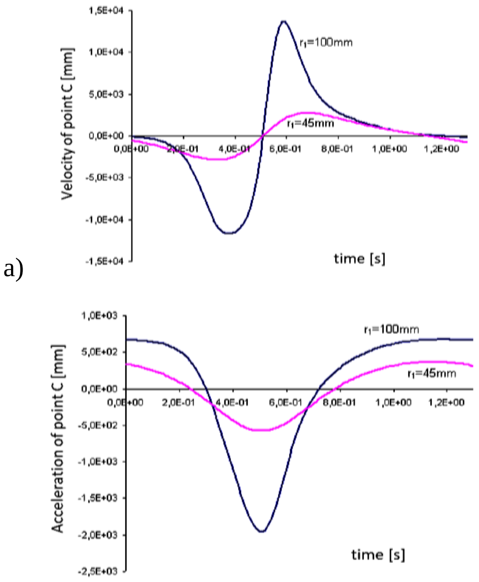
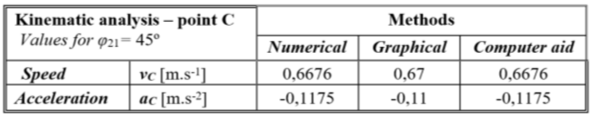


Figure 7. Comparison of the obtained dependencies on time for two different dimensions of the drive member of mechanism;
a) velocity, b) acceleration

III. Results and Discussion

The values obtained by all three approaches to kinematic analysis are presented in Tab.1. It can be said that the results are the same and so the final decision which of methods to select for the solution depends only on the investigator and his possibilities. If he is good in math, he makes the analytical choice; if he disposes of hardware and software for kinematic analysis, he can use the second method. In both cases, he has to know the basic principles of mechanics.

TABLE I. Type Sizes for Camera-Ready Papers



Kinematic analysis – point C *Values for $\varphi_{21} = 45°$*		**Methods**		
		Numerical	***Graphical***	***Computer aid***
Speed	v_C [m.s^{-1}]	0,6676	0,67	0,6676
Acceleration	a_C [m.s^{-2}]	-0,1175	-0,11	-0,1175

IV. Conclusion

Three various approaches to the kinematic analysis of the Whitworth mechanism have been introduced along with their advantages and disadvantages. Based on the achieved results can be said that they are the same and decision, which of the approach will be used by a designer depends on his skills and possibilities.

It is clear that modern trends force the designer to use the solution with computer aid because it is the most flexible to improve and to modify. By means of a virtual model, it is possible to reduce the time for analysis considerably. The simulation model allows to realize the complex processes through the use of computer in a while, which take days or weeks in real-time, and so it represents the ideal tool for the aid and the deciding on the various levels of the manufacturing. This model allows identifying the problematical points of the project, to determine the main risks of work, collisions, etc., too. That is why the simulation can be considered one of the most effective tools for decision and solution testing. [17]

On the other hand, it is also necessary to take into account that even though the virtual simulation of mechanism has a fixed place in engineering practice, it seldom corresponds to real conditions due to outside and inside influences, which can not be predicted and that can be very difficult defined in advance. The most important fact is that simulation and a computer-aided solution without the problem understanding can lead to big troubles after the project realization and loss of time or money spent on the project preparation. It can be concluded that simulation is not “panacea” for all problems. There are tasks, when it is better to apply other, the cheaper tools of problem-solving when the simulation appears as few effective. According to Pantazopoulos [18], support and access to knowledge pools and use of modern technology, IT applications, and social media/special interest groups for knowledge diffusion are of vital importance. Institutional establishment, leadership drivers, and social vision can lead to the development of strong foundations of knowledge pools and shape their future perspectives.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, methodology, supervision, software and article writing: K. Monkova.

Records, validation, resources and editing: P. Monka.

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