The Design and Simulation of Mechanisms

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Abstract: This thesis presents the study of 4-bar mechanism motion. The idea is modelling and analysing of a certain crank-rocker mechanism, researching the theoretical principles, to obtain mathematical and SolidWorks data. Subsequently, the collected values (theoretical and SolidWorks) are compared to see the efficiency of SolidWorks Simulation. During the research, the study presents theoretical calculations of general crank-rocker mechanism to achieve the main concepts of modelling the mechanism. As methods, there have been chosen Excel calculations, based on theory, and SolidWorks Motion analysis. As a result, there was obtained mathematical data and graphs of 4-bar mechanism motions (angular velocities and accelerations), showing the closely similar values.	
Keywords:	Four-bar mechanism, SolidWorks, Angular Velocity, Angular Acceleration
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LIST OF SYMBOLS

A^t – tangential acceleration, [rad/s^2]

L_1 , L_2 , L_3, L_4 – links, [mm]

θ_2 – certain crank angle, [deg]

θ_3 – interior joint angles, [deg]

θ_4 – interior joint angle, [deg]

A – linear acceleration [m/s^2]

V- linear velocity of a point [m/s]

r - distance from the center of rotation to the point, [mm]

v - magnitude of the linear velocity of the point, [mm]

ΔR – linear displacement, [mm]

$\Delta\theta$ – angular distance, [deg]

α – angular acceleration, [deg/s^2]

γ – interior joint angle [deg]

ω – angular velocity [deg/s]

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FOREWORD

First of all, I am sincerely grateful for excellent supervision and exceptional patience of my thesis supervisor Mathew Vihtonen.

I would like to thank my family for enormous support, that they gave me throughout my studies in Arcada, especially during graduating.

And I want to grate all my friends for being on my side in all life situations and encouragements in my abilities.

1. INTRODUCTION

Did you know, that mechanisms were born with the nature, as some Italian researchers describe? Simple design of legs or wings greatly represents the mechanism motion. Even movable eye could be called a mechanism.

From the ancient time, primitive men had started to use simple technologies of creating snares and traps for more efficient hunting. In a while, people were taming different animals and were adapting them into new techniques, especially after the invention of a wheel. Mechanisms were evaluating with human history, and nowadays, play small and big roles all over the world.

(Ceccareli, et al., 2010)

During the following study, the analysis of basic crank-rocker mechanism was completed. The Figure 1. illustrates the appearance of real life example.

Figure 1. The real example of crank-rocker is landing gear of airplane wheel

1.1 OBJECTIVES

For the following study, there had been targeted the following objectives of the thesis:

1. Analysis of the 4-bar mechanism, using theoretical knowledge.
2. Designing the model of 4-bar mechanism in SolidWorks software.
3. Simulation of 4-bar mechanism in SolidWorks software.
4. Compare the theoretical values (accelerations, velocities) to values obtained by SolidWorks.

1.2 SELECTION OF METHODOLOGY

In order to reach objectives of this thesis, the theoretical concepts of 4-bar mechanisms were studied. Most crucial values for the further analysis were angular displacements, angular velocities and angular accelerations. The method for collecting the theoretical data is Microsoft Excel, which was chosen for its quick and efficient capabilities in calculating and obtaining required values. Then, the SolidWorks Software was accepted as a program for designing and simulation the model of 4-bar mechanism, as it is worldwide known and give a lot of opportunities to achieve thesis objectives. Also as a default angular speed was set as 10 [rpm].

1.3 RELEVANCE TO PROGRAMME

The choice of SolidWorks Software was also connected to the fact, that it had been studied intensely during my studies at Arcada. Moreover, the concept of designing mechanisms is related with the field of my degree, due to my specialization, which is defined as “Functional materials and design”. Meanwhile my studies in Arcada, the design was the desirable stream, which was appreciating to write thesis about.

2. LITERATURE REVIEW

2.1 MECHANISM

"Give me a lever and a place to stand and I will move the Earth".

- *Archimedes*

David H. Myszka describes that, mechanisms of machines are used to convert and transit forces from one point to the other to complete some objective of machine. Therefore, Mechanism is the main part of machine. For instance, if we would consider the usual Lever (Figure 2), it is demonstrating how small input force could be amplified to larger output force. The objective of lever is gaining a mechanical advantage.

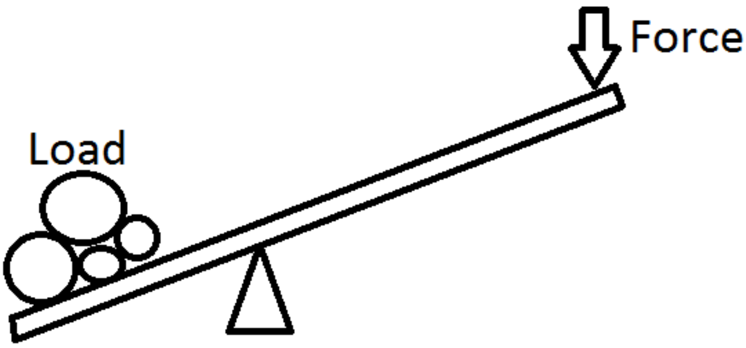


Figure 2. Schematic example of simple mechanism - Lever

Mechanisms consist of connected parts with the objective of transferring motion and force from a power source to an output (Myszka, 2012):

- Links are parts of mechanism, connected with at least two nodes, in objective to transmit motion and forces. Simple link contains only two joints, but complex links contains more.
  Links are considered to be rigid in mechanisms. They are connected with joints.
- Joint is a movable connection between two links. Primary joints could be two types: revolute (pin, hinge point) and sliding (piston, prismatic joint). Revolute joint allows rotation of connected links. The sliding joint allows linear sliding between connected

links. In addition, they are also called full joints. The other type of joints is called half joint (cam, gear joint). They have more complex motion, involving rotation and sliding. A point of interest is a point on a link where the motion is of special interest. Once kinematic analysis is performed, the displacement, velocity, and accelerations of that point are determined.

- An actuator is the component that drives the mechanism. Common actuators include motors (electric and hydraulic), engines, cylinders (hydraulic and pneumatic), ball-screw motors, and solenoids. Manually operated machines utilize human motion, such as turning a crank, as the actuator.

First of all, to analyze the mechanism, there should be defined the principles of basic science branches, which are Kinematics, Statics and Kinetics. (J.Rider, 2015)

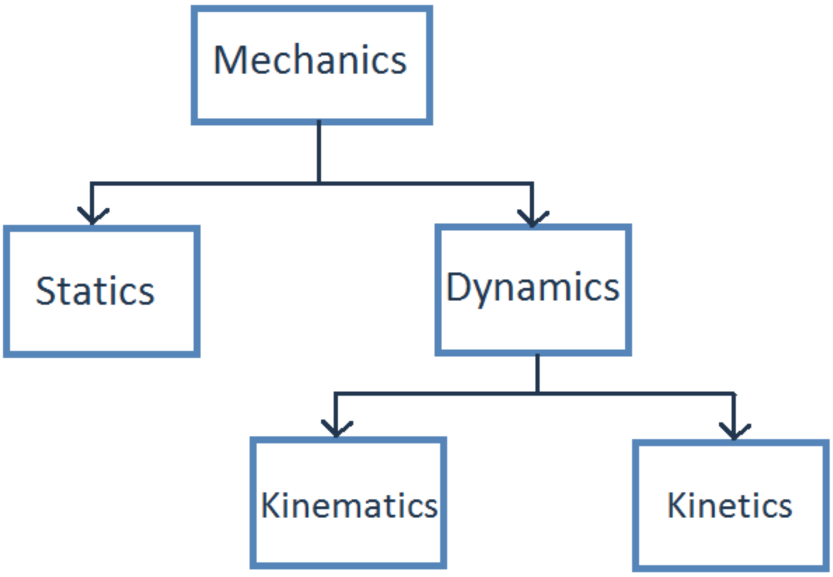


Figure 3. Diagram of Mechanics classification (J.Rider, 2015)

2.2 KINEMATICS, KINETICS, STATICS

Kinematics – study of the geometry motion, how the things move. It includes also determination of position, rotation, displacement, velocity, speed and acceleration of mechanism.

To analyze the mechanism, first thing to do is design the kinematic diagram, which represents the links of mechanism. It should be drawn to scale proportional to the analyzed mechanism.

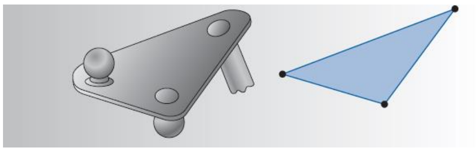


Figure 4. Example of Kinematic representation. (Myszka, 2012)

- Kinetics - study, referred to the result of forces and moments on bodies.
- Statics - study of forces and moments, separated of from motion. (J.Rider, 2015)

Absolute motion is measured with respect to a stationary frame. Relative motion is measured for one point or link with respect to another link. As David H. Myszka illustrates the process, the first step in drawing a kinematic diagram is selecting a member to serve as the frame. In some cases, the selection of a frame is arbitrary. As different links are chosen as a frame, the relative motion of the links is not altered, but the absolute motion can be drastically different. For machines without a stationary link, relative motion is often the desired result of kinematic analysis. Utilizing alternate links to serve as the fixed link is termed kinematic inversion.

2.3 PLANE MOTION

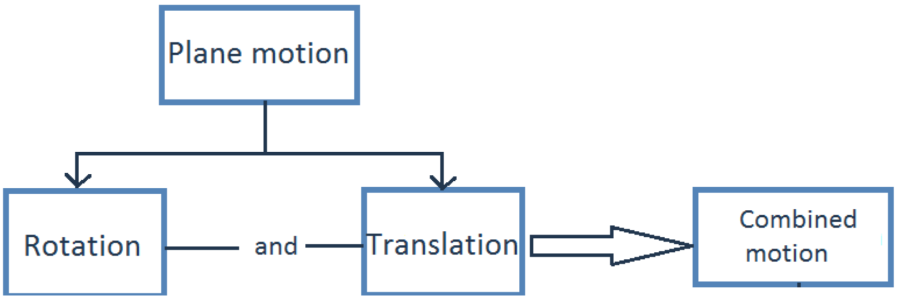


Figure 5. Diagram of classification of Plane motion (O.Barton, 1993)

Plane motion is rigid body moving in the same plane or parallel planes, as it is defined by O. Barton, 1993. During the process of motion, all points and linkages of body stay at a constant distance from a reference plane.

O. Barton includes three branches of plane motion:

- Rotation – is a motion, when one point remains stationary throughout the body moving around this point. (Figure 6)

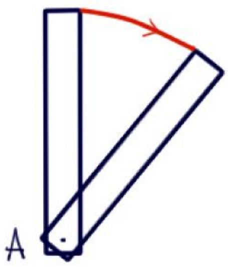


Figure 6. Rotation of point A.

- Translation – describes motion, which does not have rotation and during translation the distance between parts of the body remain the same. (Figure 7)

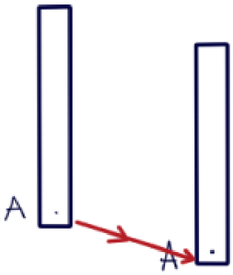


Figure 7. Translation of point B.

- Combined motion – is a translation and rotation motions, combined together, in the body movement. (Figure 8)

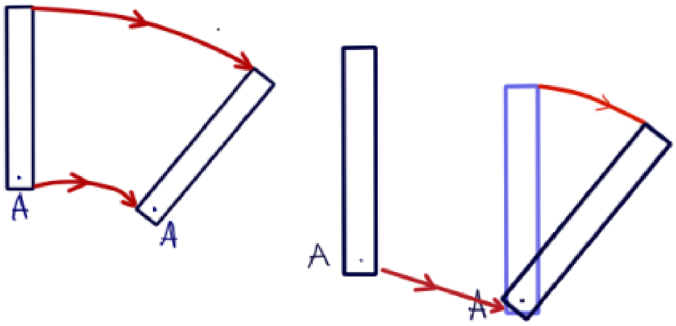


Figure 8. Combined motion of point A.

2.4 MOBILITY

The next important study of analyzing the mechanism is its mobility. Mobility defines the linkage degrees of freedom, which is the number of actuators needed to operate the mechanism. The symbol of mobility is *M* and it could be calculated through the Gruebler's Equation.

$$M = 3 \times (N - 1) - 2j_p - j_h\,, \quad (1)$$

where:

M – degrees of freedom

N – total number of links, including ground

jp - total number of primary joints (full joints)

jh - total number of higher-order joints (half joints)

(Myszka, 2012)

2.4.1 The four-bar mechanism

The Four-Bar mechanism is the easiest and most often linkage. It is chain of pin-collected links, that allows relative motion between the links. One of links is designated as a frame.

The mobility of a 4-bar mechanism is:

$$M = 3 \times (N - 1) - 2j_p - j_h = 3 \times (4 - 1) - 2(4) - 0 = 1 \quad (2)$$

As it was calculated, it has one degree of freedom, as a result it demonstrates that 4-bar mechanism is fully operated with one driver.

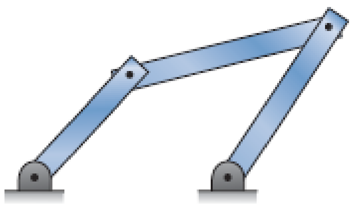


Figure 9. Degree of freedom (M=1) of 4-bar mechanism, (Myszka, 2012)

The frame link is unable to move and usually it called the input link. The link that is attached to the frame is termed as the output link. The coupler connects the motion of the input to the output links.

(Myszka, 2012)

2.4.2 Grashof's equation

As Myszka explains, the Grashof's equation states that a 4-bar mechanism has at least one revolving link (will rotate trough 360^0) if:

$S + L \leq P + Q,$ *(3)*

where:

S – shortest link

L – longest link

P, Q – other two links

If the Grashof's equation is not true, then no will rotate through 360^0.

Categories of 4-bar mechanisms:

Table 1. 4-bar mechanisms categories (Myszka, 2012)

Criteria	Shortest Link	Category
$S + L < P + Q$	Frame	Double crank
$S + L < P + Q$	Side	Crank-rocker
$S + L < P + Q$	Coupler	Double rocker
$S + L \leq P + Q$	Any	Change point
$S + L > P + Q$	Any	Triple rocker

2.5 POSITION ANALYSIS

2.5.1 Position of a point

Position is a term of the location of an object, if it is a point. The position of a point on a mechanism can be specified by its distance from predefined origin and angle from a reference axis. Alternately, if we work in the polar coordinate system, then we identify the position of a point by its rectangular components of the position vector. (J.Rider, 2015)

2.5.2 Angular Position of a Link

An angular position, θ, is defined as the angle a line between two points on that link forms with a reference axis.

Angular Position is specified by J. Rider:

- As positive, if the angle is measured counterclockwise from the reference axis.
- As negative, if the angle is measured as clockwise from the reference axis.

2.5.3 Position of a Mechanism

The main objective of analyzing a mechanism is to study its motion. Motion proceeds, as the position of links is changed and happens the moving of mechanism configuration by forces.

2.5.4 Position: analytical analysis

To collect results with a high degree of accuracy, we use analytical methods in the position analysis, defined by Myszka. During analyzing the mechanisms in this thesis, there would be used triangle method of position analysis.

Triangle method includes fitting reference lines within a mechanism and studying the triangles.

The detailed using of triangle method for a 4-bar linkage is demonstrated in the following topic.

2.5.6 Position Equations for a Four-Bar Linkage

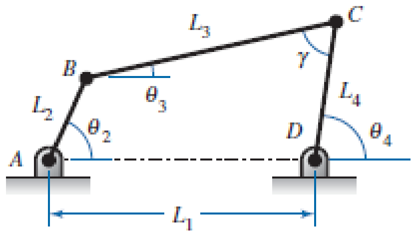


Figure 10. Illustration of 4-bar linkage (Myszka, 2012)

θ_2 – certain crank angle,

$\theta_3, \theta_4, \gamma$ – interior joint angles

L_1 , L_2 , L_3, L_4 – links

$$BD = \sqrt{L_1^2 + L_2^2 - 2 \cdot L_1 \cdot L_2 \cos\theta_2} \quad [\text{m}] \qquad (4)$$

$$\gamma = \cos^{-1}\left[\frac{(L_3)^2+(L_4)^2-(BD)^2}{2 \cdot L_3 \cdot L_4}\right] \qquad (5)$$

$$\theta_3 = 2\tan^{-1}\left[\frac{-L_2 \cdot \sin\theta_2 + L_4 \sin\gamma}{L_1 + L_3 - L_2 \cdot \cos\theta_2 - L_4 \cos\gamma}\right] \qquad (6)$$

$$\theta_4 = 2\tan^{-1}\left[\frac{L_2 \cdot \sin\theta_2 - L_3 \sin\gamma}{L_2 \cdot \cos\theta_2 + L_4 - L_1 - L_3 \cos\gamma}\right] \qquad (7)$$

The equations are applicable to any four-bar mechanism configuration. (Myszka, 2012)

2.6 DISPLACEMENT

In the following chapter, Myszka explains displacement as a vector, which distance is between the starting and ending position of a point or a link.

There are two types of displacement: linear and angular.

- ΔR – linear displacement, which shows distance between the starting and ending position of a point during a time interval.
- $\Delta\theta$ – is the angular distance between two figures of a rotating link.

$\Delta\theta = \theta_1 - \theta$, which magnitude will be in rotational units, for instance degrees, radians. The direction is defined by its clockwise or counterclockwise position.

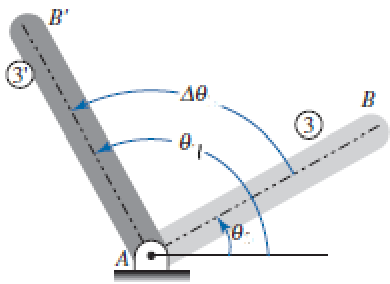


Figure 11. Angular displacement (Myszka, 2012)

2.7 VELOCITY ANALYSIS

To start with, during manufacturing of a machine, the timing is critical. Therefore, as velocity refers to the movement of a point of a mechanism with time, velocity analysis is essential. To calculate the velocity there could be used common analysis way. (Myszka, 2012)

Linear velocity method:

- V- linear velocity of a point. It is defined as a linear displacement of that point per t, time.

  ΔR- vector, which refers to a change in position of that point.

  Linear displacement of a point could be calculated with the following formula:

  $$V = \lim_{\Delta_t \to 0} \frac{dR}{dt}. \qquad (8)$$

  Therefore, if time is short period, velocity could be calculated by:

  $$V \cong \frac{\Delta R}{\Delta t}, \ [m/s] \qquad (9)$$

  To completely define the velocity, as a vector, a direction is also required. The direction of relative linear velocity is always perpendicular to the line between the axis of rotation and the point and has the direction of angular velocity.

- Angular velocity, ω, is the angular displacement of that link per unit of time, t.

From a displacement theory topic, we use rotational displacement of a link, $\Delta\theta$, to calculate the angular velocity via formula:

$$\omega = \lim_{\Delta t \to 0} \frac{\Delta\theta}{\Delta t} = \frac{d\theta}{dt}, \qquad (10)$$

For short time intervals:

$$\omega \cong \frac{\Delta\theta}{\Delta t}. \qquad (11)$$

The common units used are [rad/s].

- To define the magnitude of the linear velocity of any point for a link in pure rotation, tangential velocity, the relationship between linear and angular velocities is used.

$v = r\omega$, where: *(12)*

v - magnitude of the linear velocity of the point [m/s].

r - distance from the center of rotation to the point [mm].

ω - angular velocity of the rotating link that contains the point [rad/s].

(Myszka, 2012) (J.Rider, 2015)

2.7.1 Velocity calculations for 4-bar mechanism

We use the theory of "Position Equations for a Four-Bar Linkage" and illustration of Figure 10 to determine the velocities of links.

θ_2 – certain crank angle,

$\theta_3, \theta_4, \gamma$ – interior joint angles

L_1, L_2, L_3, L_4 – links

$$BD = \sqrt{L_1^2 + L_2^2 - 2 \cdot L_1 \cdot L_2 \cos\theta_2} \ \text{[m]}$$

$$\gamma = \cos^{-1}\left[\frac{(L_3)^2 + (L_4)^2 - (BD)^2}{2 \cdot L_3 \cdot L_4}\right]$$

$$\theta_3 = 2\tan^{-1}\left[\frac{-L_2 \cdot \sin\theta_2 + L_4 \sin\gamma}{L_1 + L_3 - L_2 \cdot \cos\theta_2 - L_4 \cos\gamma}\right]$$

$$\theta_4 = 2\tan^{-1}\left[\frac{L_2 \cdot \sin\theta_2 - L_3 \sin\gamma}{L_2 \cdot \cos\theta_2 + L_4 - L_1 - L_3 \cos\gamma}\right]$$

$$\omega_3 = -\omega_2 \left[\frac{L_2 \sin(\theta_4 - \theta_2)}{L_3 \sin\gamma}\right] \text{[rad/s]} \quad (13)$$

$$\omega_4 = -\omega_2 \left[\frac{L_2 \sin(\theta_3 - \theta_2)}{L_4 \sin\gamma}\right] \text{[rad/s]} \quad (14)$$

(Myszka, 2012)

2.8 ACCELERATION ANALYSIS

Acceleration analysis is important part due to representation of inertial forces. In addition, inertia forces are proportional to the rectilinear acceleration and inertia torques are proportional to angular acceleration imposed on the body. The method of acceleration analysis is similar to the relative velocity method, that was introduced earlier. (J.Rider, 2015)

2.8.1 Linear Acceleration of Rectilinear Points

Relative acceleration is the study of one point relative to another on a straight line. In common, such a linkage is attached to the frame with the sliding joint. In this case, velocity magnitude changes only.

Acceleration is calculated with these formulas:

$$A = \lim_{\Delta t \to 0} \frac{\Delta V}{\Delta t} = \frac{dv}{dt} \quad \rightarrow$$

$$V = \frac{dR}{dt} \quad \rightarrow$$

$$A = \frac{d^2R}{dt^2}$$

For short time periods:

$A \cong \frac{\Delta V}{\Delta t}$ *(15)*

Linear acceleration unit is [m/s^2].

Velocity change that appears in the period of constant acceleration is calculated with:

$\Delta V = v_{final} - v_{initial} = A\Delta t$ *(16)*

Displacement change that appears in the period of constant acceleration is calculated with:

$\Delta R = \frac{1}{2}A\Delta t^2 + v_{initial}\Delta t$ *(17)*

Combining the velocity change and displacement change formulas we get:

$\left(V_{final}\right)^2 = (V_{initial})^2 + 2A\Delta R$ *(18)*

(Myszka, 2012)

2.8.2 Angular Acceleration

Angular acceleration is a term referring to rotational motion of a link about the point with linear motion. It is defined as angular velocity of a link per unit of time and calculated as:

$\alpha = \lim_{\Delta t \to 0} \frac{\Delta\omega}{\Delta t} = \frac{d\omega}{dt}$

As $\omega = \frac{d\theta}{dt}$ $\rightarrow$

$\alpha = \frac{d^2\theta}{dt^2}$ *(19)*

For short time periods:

$\alpha \cong \frac{\Delta\omega}{\Delta t}$ [rad/s^2] *(20)*

(Myszka, 2012)

2.8.3 Linear Acceleration of a general point

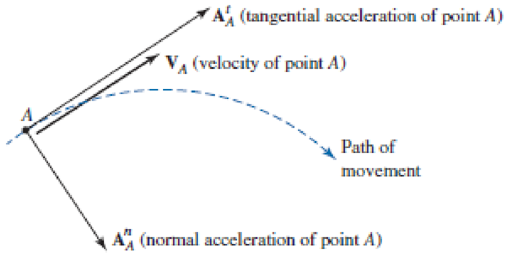


Figure 12. Acceleration of point A. (Myszka, 2012)

For a point moving in a common case its velocity could change in two ways:

1. The magnitude of the velocity changes. In that case acceleration occurs in the path of motion and is defined as tangential acceleration, A^t.

   Mathematically tangential acceleration of point A on a rotating link 2 is expressed:

   $$A_A^t = \frac{dV_A}{dt} = \frac{d(\omega_2 R_{OA})}{dt} = R\frac{d\omega_2}{dt} = R_{OA}\alpha_2 \qquad (21)$$

2. The direction of the velocity vector changes over time. As the link acts the rotational motional at the associated point, it causes a centrifugal acceleration that is perpendicular to the motion path direction. It is defined as normal acceleration, A^n. It is always directed toward the link rotation center.

   To calculate the magnitude of normal acceleration point A on a rotating link 2, we use the relationships between equations of the linear velocity and angular velocity.

   $$A_A^n = V_A\omega_2 = (\omega_2 R_{OA})\omega_2 = \omega_2^2 R_{OA} = V_A\left(\frac{V_A}{R_{OA}}\right) = \frac{V_A^2}{R_{OA}} \qquad (22)$$

(Myszka, 2012)

2.8.4 Total Acceleration

Total acceleration of a body is proportional to inertial forces. It is a vector resultant of the tangential and normal acceleration components.

$$A_A = A_A^n + A_A^t \qquad (23)$$

(Myszka, 2012)

2.8.5 Acceleration analysis for 4-bar mechanism

We use the Myszka's theory of "Position Equations for a Four-Bar Linkage", "Velocity calculations for 4-bar mechanism" and illustration of Fig.9 to determine the acceleration of links.

θ_2 – certain crank angle,

$\theta_3, \theta_4, \gamma$ – interior joint angles

L_1, L_2, L_3, L_4 – links

$$BD = \sqrt{L_1^2 + L_2^2 - 2 \cdot L_1 \cdot L_2 \cos\theta_2}$$

$$\gamma = \cos^{-1}\left[\frac{(L_3)^2 + (L_4)^2 - (BD)^2}{2 \cdot L_3 \cdot L_4}\right]$$

$$\theta_3 = 2\tan^{-1}\left[\frac{-L_2 \cdot \sin\theta_2 + L_4 \sin\gamma}{L_1 + L_3 - L_2 \cdot \cos\theta_2 - L_4 \cos\gamma}\right]$$

$$\theta_3 = 2\tan^{-1}\left[\frac{L_2 \cdot \sin\theta_2 - L_3 \sin\gamma}{L_2 \cdot \cos\theta_2 + L_4 - L_1 - L_3 \cos\gamma}\right]$$

$$\omega_3 = -\omega_2\left[\frac{L_2 \sin(\theta_4 - \theta_2)}{L_3 \sin\gamma}\right]$$

$$\omega_4 = -\omega_2\left[\frac{L_2 \sin(\theta_3 - \theta_2)}{L_4 \sin\gamma}\right]$$

Acceleration equations calculations:

$$\alpha_3 = \frac{\alpha_2 L_2 \sin(\theta_2 - \theta_4) + \omega_2^2 L_2 \cos(\theta_2 - \theta_4) - \omega_4^2 L_4 + \omega_3^2 L_3 \cos(\theta_4 - \theta_3)}{L_3 \sin(\theta_4 - \theta_3)} \text{ [rad/s}^2\text{]} \qquad (24)$$

$$\alpha_4 = \frac{\alpha_2 L_2 \sin(\theta_2 - \theta_3) + \omega_2^2 L_2 \cos(\theta_2 - \theta_3) + \omega_3^2 L_3 - \omega_3^2 L_4 \cos(\theta_4 - \theta_3)}{L_4 \sin(\theta_4 - \theta_3)} \text{ [rad/s}^2\text{]} \qquad (25)$$

(Myszka, 2012)

2.9 SOLIDWORKS

SolidWorks is a solid modeling computer-aided design and computer-aided engineering software. It is designed for parametric feature-based approach for manufacturing products at first steps of modelling and simulating. The software runs on Microsoft Windows. It is published by

Dassault Systemes. SolidWorks provides the development of products of any complexity and purpose. (SolidWorks, 2018)

From Russian version of Wikipedia - as there was not another source of information - we obtain information about The SolidWorks software packages, which include basic configurations of SolidWorks Standard, SolidWorks Professional, SolidWorks Premium, and various application modules:

- Engineering data management: SolidWorks Enterprise PDM
- Engineering calculations: SolidWorks Simulation Professional, SolidWorks Simulation Premium, SolidWorks Flow Simulation
- Electrical Engineering: SolidWorks Electrical
- Development of online documentation: SolidWorks Composer
- Machining, CNC: CAMWorks
- Verification of UE: CAMWorks Virtual Machine
- Quality control: SolidWorks Inspection
- Uncircular technologies: SolidWorks MBD etc.

SolidWorks supports the Microsoft Structured Storage file format - SLDDRW (drawing files), SLDPRT (part files), SLDASM (assembly files) file, including preview bitmaps and metadata sub-files. (SolidWorks, 2018)

3. METHOD

To start with, the main objective of my thesis is analyzing 4-bar mechanism, using the theory, presented above to compare the values obtained throughout hand calculations to values obtained by simulation in SolidWorks software.

Figure 13. illustrate the sketch of mechanism, which was used in following calculations.

$L_1 = 60$, $L_2 = 25$, $L_3 = 70$, $L_4 = 45$ [mm]

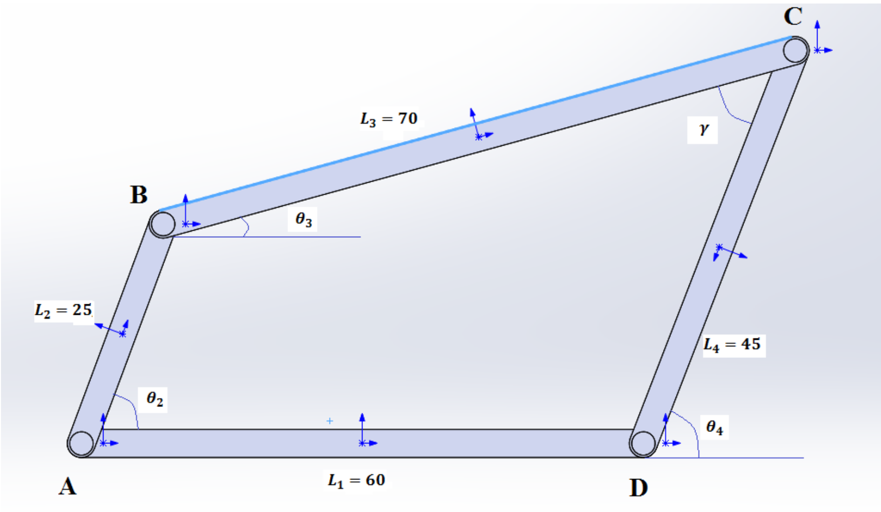


Figure 13. Sketch of used mechanism

3.1 Calculations

For analyzing 4-bar mechanism there had been chosen, which is also defined as Crank-rocker mechanism.

In Crank-rocker formula is introduced as:

$S + L < P + Q$

We insert dimensions of our links in the equation:

$25 + 70 < 60 + 45;$

$95 < 105$, which determines, the link dimensions of our mechanism satisfy required concepts of Crank-rocker mechanism. (Myszka, 2012, p. 21)

Crank-rocker is a 4-bar mechanism, which shortest link is connected to the frame. The shortest link is defined as “crank” and has continuous rotation. The “rocker” is output link of mechanism and it oscillates between two limiting angles. Those two limiting angles is also called as “dead-center” positions.

(Myszka, 2012) See Figure 14.

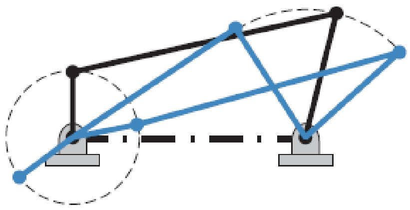


Figure 14. Illustration of Crank-rocker, (Myszka, 2012)

3.1.1 Calculate Mobility

To calculate the mobility, it was determined that there are four links in this mechanism and four pin joints. Therefore,

$N = 4$, $j_p = 4$ pins, $j_h = 0$.

$$M = 3 \times (N-1) - 2j_p - j_h = 3 \times (4-1) - 2(4) - 0 = 1$$

With one degree of freedom, if we move L_2, it set precisely positions of other links in the mechanism.

3.1.2 Theoretical calculations to find angle values

During following calculations, we are using and the formulas from 2.5.6 Position Equations for a Four-Bar Linkage chapter.

Firstly, we set links and angle values.

$L_1 = 60, L_2 = 25, L_3 = 70, L_4 = 45$ [mm]

$\theta_2 = 90^0$. (We choose this magnitude for convenient theoretical calculations, in the following Excel chapters there would be calculated also $0^0 \leq \theta_2 \leq 360^0$)

$$BD = \sqrt{L_1^2 + L_2^2 - 2 \cdot L_1 \cdot L_2 \cos\theta_2} = \sqrt{60^2 + 25^2 - 2 \cdot 60 \cdot 25 \cdot \cos 90^0} = 65 \text{ [mm]}$$

$$\gamma = cos^{-1}\left[\frac{(L_3)^2+(L_4)^2-(BD)^2}{2\cdot L_3\cdot L_4}\right] = \cos^{-1}\left[\frac{(70)^2+(45)^2-(65)^2}{2\cdot 70\cdot 45}\right] = 64{,}62°$$

$$\theta_3 = 2\tan^{-1}\left[\frac{-L_2\cdot\sin\theta_2 + L_4\sin\gamma}{L_1 + L_3 - L_2\cdot\cos\theta_2 - L_4\cos\gamma}\right]$$

$$= 2\tan^{-1}\left[\frac{-25\cdot\sin 90^0 + 45\sin 64{,}62°}{60+70-25\cdot\cos 90^0 - 45\cos 64{,}62°}\right] = 16{,}1°$$

$$\theta_4 = 2\tan^{-1}\left[\frac{L_2\cdot\sin\theta_2 - L_3\sin\gamma}{L_2\cdot\cos\theta_2 + L_4 - L_1 - L_3\cos\gamma}\right]$$

$$= 2\tan^{-1}\left[\frac{25\cdot\sin 90^0 - 70\sin 64{,}62°}{25\cdot\cos 90^0 + 45 - 60 - 70\cos 64{,}62°}\right] = 80{,}72°$$

3.1.3 Theoretical calculations to find angle values with using Excel

Previously, the angle values for our mechanism were found using $\theta_2 = 90^0$. The following Excel table introduces changing of angle values with $0^0 \le \theta_2 \le 360^0$.

$L_1 = 60$, $L_2 = 25$, $L_3 = 70$, $L_4 = 45$ [mm]

For the Excel calculation we apply angular velocity calculations used in previous chapter.

Table 2. .Angle values displacement

Angle, θ_2, deg	**BD, mm**	**Angle, γ, deg**	**Angle, θ_3, deg**	**Angle, θ_4, deg**
0	35,00	25,21	33,20	58,41
30	40,34	32,76	19,08	51,84
60	52,20	48,19	15,48	63,67
90	65,00	64,62	16,10	80,72
120	75,66	79,02	19,09	98,11
150	82,60	89,07	24,30	113,37
180	85,00	92,73	31,93	124,65
210	82,60	89,07	41,71	130,78
240	75,66	79,02	52,35	131,37
270	65,00	64,62	61,34	125,96
300	52,20	48,19	64,48	112,67
330	40,34	32,76	55,19	87,94

Angle, θ_2, deg	BD, mm	Angle, γ, deg	Angle, θ_3, deg	Angle, θ_4, deg
360	35,00	25,21	33,20	58,41

For the following data comparison, the magnitude of θ_4 should be changed. SolidWorks determines the θ_4 as inner angle in subsequent Motion simulations and in Excel theoretical calculations we used the outer angle, see Table 3.

To get demonstrative results, we subtract θ_4 values from 180^0 and use them in following calculations in Excel and SolidWorks.

Table 3. The SolidWorks and theoretical angle magnitude

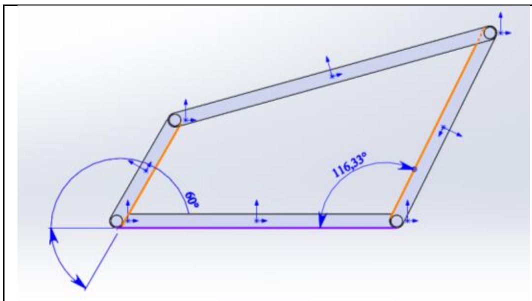
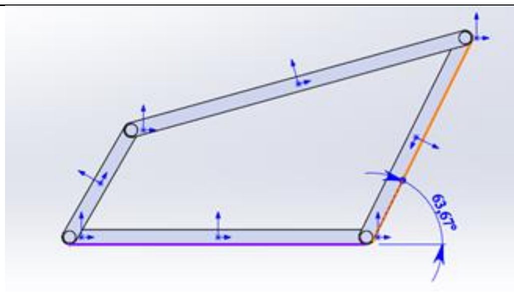
	
θ_4 in SolidWorks	θ_4 in Excel

Table 4. Angles values, representing the calculated magnitudes

Angle, θ_2, deg	Angle, θ_3, deg	Angle, θ_4, deg (outer)	Angle, θ_4, deg (inner)
0	33,20	58,41	-121,59
30	19,08	51,84	-128,16
60	15,48	63,67	-116,33
90	16,10	80,72	-99,28
120	19,09	98,11	-81,89
150	24,30	113,37	-66,63
180	31,93	124,65	-55,35
210	41,71	130,78	-49,22
240	52,35	131,37	-48,63
270	61,34	125,96	-54,04
300	64,48	112,67	-67,33
330	55,19	87,94	-92,06
360	33,20	58,41	-121,59

The following graph shows how angular displacement behavior of angles θ_3 and θ_4 changes related to θ_2 angle.

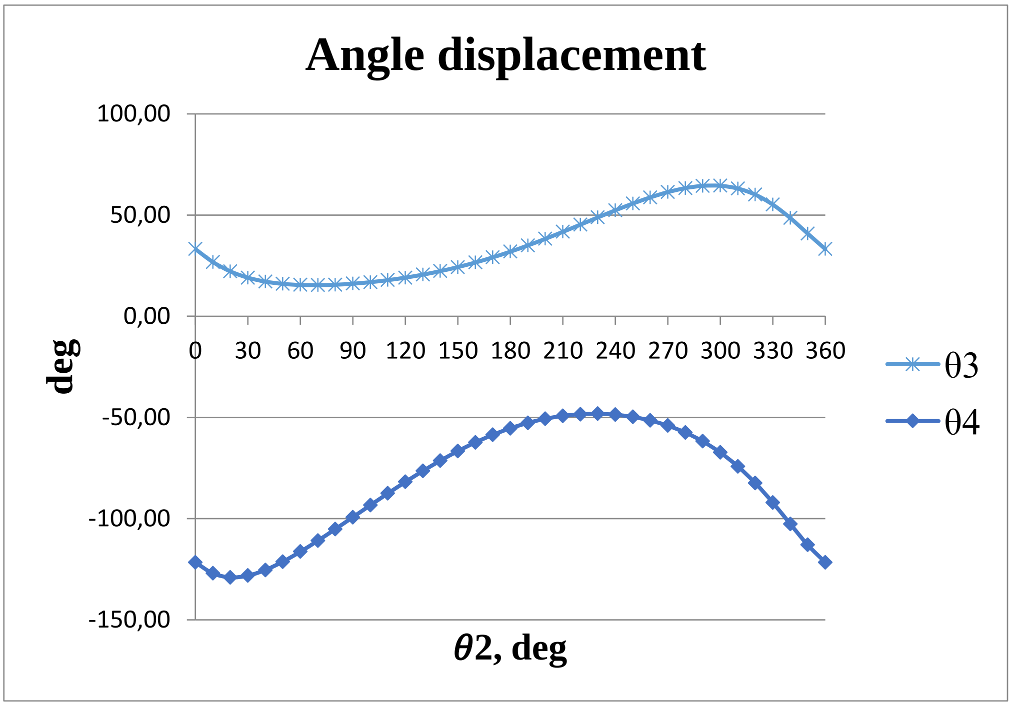


Figure 15. Graph of angle displacement

3.1.4 Theoretical angular velocity calculations

As in previous chapter, we use same link and angle values, but add value of ω_2 and use obtained angle dimensions.

$L_1 = 60, L_2 = 25, L_3 = 70, L_4 = 45$ [mm]

$\theta_2 = 90^0, \theta_3 = 16{,}1°, \theta_4 = 80{,}72°, \gamma = 64{,}62°$

$\omega_2 = 10$ [rpm]

For following calculations, we convert the ω_2 from [rpm] magnitude to [rad/s]. We use conversion method introduced by Myszka. (Myszka, 2012, p. 126)

$\omega_2[rpm] = \frac{60}{2\pi} \cdot \omega_2[rad/s] = 1{,}05$

$\omega_2 = 1{,}05$ [rad/s]

$\omega_3 = -\omega_2 \left[\frac{L_2 \sin(\theta_4 - \theta_2)}{L_3 \sin\gamma}\right] = -1{,}05 * \left[\frac{25 * sin(80{,}72 - 90)}{70 * sin\, 64{,}62}\right] = 0{,}07$ [rad/s]

$$\omega_4 = -\omega_2 \left[\frac{L_2 \sin(\theta_3 - \theta_2)}{L_4 \sin\gamma}\right] = -1{,}05 * \left[\frac{25*\sin(16{,}1-90)}{45*\sin 64{,}62}\right] = 0{,}62 \text{ [rad/s]}$$

3.1.4 Theoretical calculations to find angular velocities with using Excel

The following Excel table introduces changing of velocities values with $0^0 \leq \theta_2 \leq 360^0$.

$L_1 = 60$, $L_2 = 25$, $L_3 = 70$, $L_4 = 45$ [mm]

For the Excel calculation we apply angular velocity calculations used in previous chapter.

Table 5. Velocities Excel calculations

Angle, θ_2, deg	**BD, mm**	**Angle, γ, deg**	**Angle, θ_3, deg**	**Angle, θ_4, deg**	**Angular velocity, ω_3, rad/s**	**Angular velocity, ω_4, rad/s**
0	35,00	25,21	33,20	58,41	-0,75	-0,75
30	40,34	32,76	19,08	51,84	-0,26	0,20
60	52,20	48,19	15,48	63,67	-0,03	0,55
90	65,00	64,62	16,10	80,72	0,07	0,62
120	75,66	79,02	19,09	98,11	0,14	0,58
150	82,60	89,07	24,30	113,37	0,22	0,47
180	85,00	92,73	31,93	124,65	0,31	0,31
210	82,60	89,07	41,71	130,78	0,37	0,12
240	75,66	79,02	52,35	131,37	0,36	-0,08
270	65,00	64,62	61,34	125,96	0,24	-0,31
300	52,20	48,19	64,48	112,67	-0,06	-0,64
330	40,34	32,76	55,19	87,94	-0,61	-1,07
360	35,00	25,21	33,20	58,41	-0,75	-0,75

For correct comparison with SolidWorks Software we need to convert Velocities values of [rad/s] into [degree/s]. To calculate this, the Velocities values would be multiplied by 180 and divided in π value. We complete this procedure in Excel. The following Excel table represents converted Velocities values with Graph illustrations.

In addition, in Excel software there have been used “ABS function” to return obtained data to the absolute values for successive comparison with SolidWorks data, see Table 5. Velocities Excel calculationsTable 5.

Table 6. Velocities Excel calculations - Absolute values

Angle, θ_2, deg	**Angular velocity, ω_3, rpm**	**Angular velocity, ω_4, rpm**	**ABS, angular velocity, (ω_3), deg/sec**	**ABS, angular velocity, (ω_4), deg/sec**
0	-0,75	-0,75	42,86	42,86
30	-0,26	0,20	14,73	11,67
60	-0,03	0,55	1,84	31,36
90	0,07	0,62	3,82	35,45
120	0,14	0,58	8,14	33,34
150	0,22	0,47	12,79	27,07
180	0,31	0,31	17,65	17,65
210	0,37	0,12	21,05	6,77
240	0,36	-0,08	20,68	4,52
270	0,24	-0,31	13,93	17,69
300	-0,06	-0,64	3,67	36,86
330	-0,61	-1,07	34,99	61,39
360	-0,75	-0,75	42,86	42,86

The following graph shows how behavior of angular velocities ω_3 and ω_4 changes related to θ_2 angle.

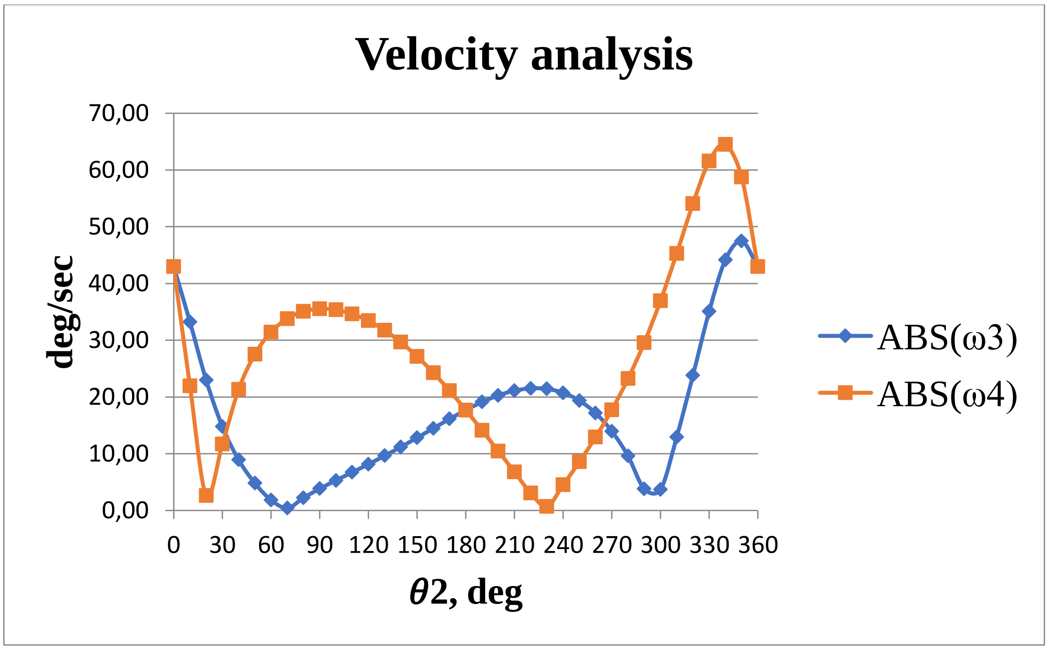


Figure 16. Velocity analysis in [degree/s]

3.1.5 Theoretical angular accelerations calculations

For the accelerations determination we use equations from “2.8.5 Acceleration analysis for 4-bar mechanism” and obtained angular velocities with already known links and angle values. In addition, we set value of α_2.

$L_1 = 60$, $L_2 = 25$, $L_3 = 70$, $L_4 = 45$ [mm]

$\theta_2 = 90^0$, $\theta_3 = 16{,}1°$, $\theta_4 = 80{,}72°$, $\gamma = 64{,}62°$

$\omega_2 = 1{,}05$ [rad/s], $\omega_3 = 0{,}07$ [rad/s], $\omega_4 = 0{,}62$[rad/s]

As value of ω_2 is constant, then $\alpha_2 = 0$ [rad/s^2]

$$\alpha_3 = \frac{\alpha_2 L_2 \sin(\theta_2-\theta_4)+\omega_2^2 L_2 \cos(\theta_2-\theta_4)-\omega_4^2 L_4+\omega_3^2 L_3 \cos(\theta_4-\theta_3)}{L_3 \sin(\theta_4-\theta_3)} =$$

$$\frac{0*25*sin(90-80{,}72)+1{,}05\ ^2*25*cos(90-80{,}72)-0{,}62^2\ *45+0{,}07^2*70*cos(80{,}72-16{,}1)}{70*sin(80{,}72-16{,}1)} = 0{,}16 \quad \text{[rad/s}^2\text{]}$$

$$\alpha_4 = \frac{\alpha_2 L_2\, sin(\theta_2-\theta_3)+\omega_2^2 L_2\, cos(\theta_2-\theta_3)+\omega_3^2 L_3-\omega_3^2 L_4\, cos(\theta_4-\theta_3)}{L_4\, sin(\theta_4-\theta_3)} =$$

$$\frac{0*25*\sin(90-77{,}69)+1{,}05\ ^2*25*\cos(90-16{,}1)+0{,}07^2*70-0{,}07^2*45\cos(80{,}72-16{,}1)}{45*\sin(80{,}72-16{,}1)} = 0{,}19 \quad \text{[rad/s}^2\text{]}$$

3.1.6 Theoretical calculations to find angular accelerations with using Excel

The following Excel table introduces changing of accelerations values with $0^0 \leq \theta_2 \leq 360^0$.

$L_1 = 60$, $L_2 = 25$, $L_3 = 70$, $L_4 = 45$ [mm]

For the Excel calculation we apply angular acceleration calculations used in previous chapter.

Table 7. Accelerations Excel calculations

Angle, θ_2, deg	**Angle, θ_3, deg**	**Angle, θ_4, deg**	**Angular velocity, ω_3, rad/s**	**Angular velocity, ω_4, rad/s**	**Angular acceleration, α_3, rad/s^2**	**Angular acceleration, α_4, rad/s^2**
0	33,20	58,41	-0,75	-0,75	0,83	2,05
30	19,08	51,84	-0,26	0,20	0,73	1,19
60	15,48	63,67	-0,03	0,55	0,27	0,58
90	16,10	80,72	0,07	0,62	0,16	0,19
120	19,09	98,11	0,14	0,58	0,15	-0,09

Angle, θ_2, deg	Angle, θ_3, deg	Angle, θ_4, deg	Angular velocity, ω_3, rad/s	Angular velocity, ω_4, rad/s	Angular acceleration, α_3, rad/s^2	Angular acceleration, α_4, rad/s^2
150	24,30	113,37	0,22	0,47	0,17	-0,28
180	31,93	124,65	0,31	0,31	0,16	-0,37
210	41,71	130,78	0,37	0,12	0,07	-0,39
240	52,35	131,37	0,36	-0,08	-0,11	-0,43
270	61,34	125,96	0,24	-0,31	-0,39	-0,52
300	64,48	112,67	-0,06	-0,64	-0,87	-0,46
330	55,19	87,94	-0,61	-1,07	-1,12	0,59
360	33,20	58,41	-0,75	-0,75	0,83	2,05

Due to the fact, that SolidWorks shows the results of accelerations in Motion Analysis with [degree/s^2] values, for correct comparison we need to convert Velocities values of [rad/s] into [degree/s^2]. To calculate this, the Accelerations values would be multiplied by 180 and divided in π value. We complete this procedure in Excel.

In addition, in Excel software there have been used “ABS function” to return obtained data to the absolute values for successive comparison with SolidWorks data.

Table 8. Accelerations Excel calculations - Absolute values

Angle, θ_2, deg	Angular acceleration, α_3, rad/s^2	Angular acceleration, α_4, rad/s^2	ABS, angular acceleration, (α_3), deg/s^2	ABS, angular acceleration, (α_4), deg/s^2
0	0,83	2,05	47,31	117,56
30	0,73	1,19	41,56	68,35
60	0,27	0,58	15,29	33,46
90	0,16	0,19	9,03	11,03
120	0,15	-0,09	8,73	5,12
150	0,17	-0,28	9,83	15,98
180	0,16	-0,37	9,02	20,94
210	0,07	-0,39	3,81	22,27
240	-0,11	-0,43	6,09	24,86

Angle, θ_2, deg	Angular acceleration, α_3, rad/s^2	Angular acceleration, α_4, rad/s^2	ABS, angular acceleration, (α_3), deg/s^2	ABS, angular acceleration, (α_4), deg/s^2
270	-0,39	-0,52	22,39	29,68
300	-0,87	-0,46	50,11	26,24
330	-1,12	0,59	64,37	33,63
360	0,83	2,05	47,31	117,56

The following graph shows, how behavior of angular accelerations α_3 and α_4 changes related to θ_2 angle.

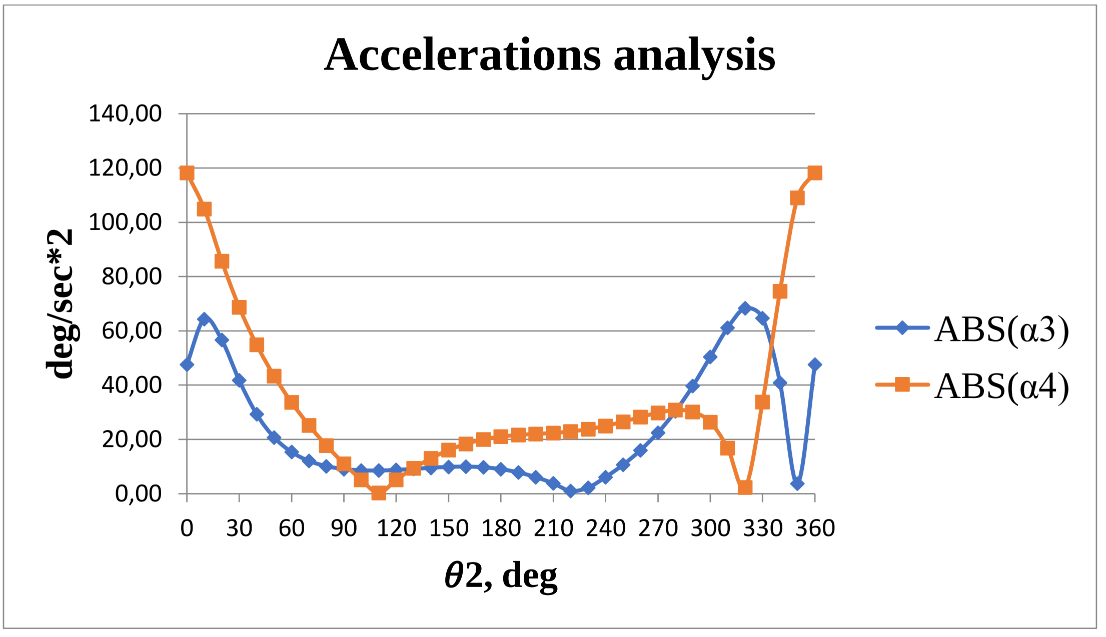


Figure 17. Accelerations analysis in [degree/s]

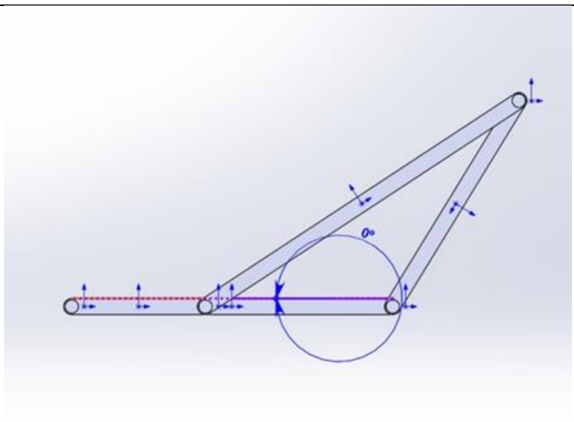
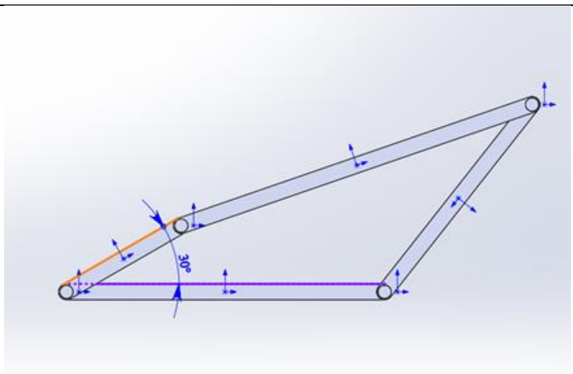
3.2 SOLIDWORKS

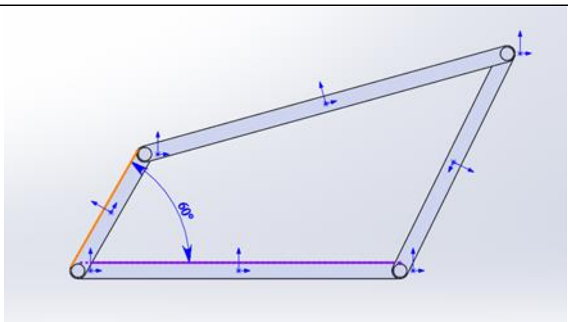
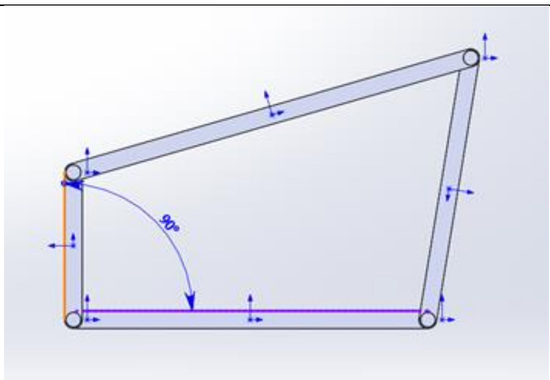
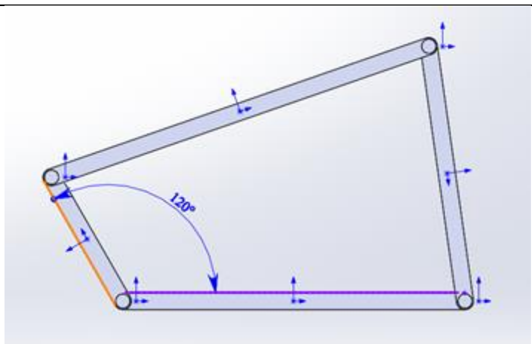
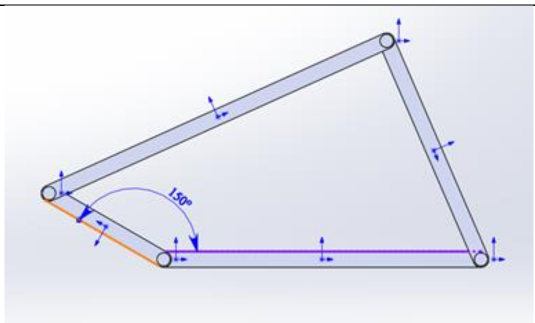
In the following chapters there would be introduced the studied 4-bar mechanism design in creating parts of model and its simulation in the SolidWorks software.

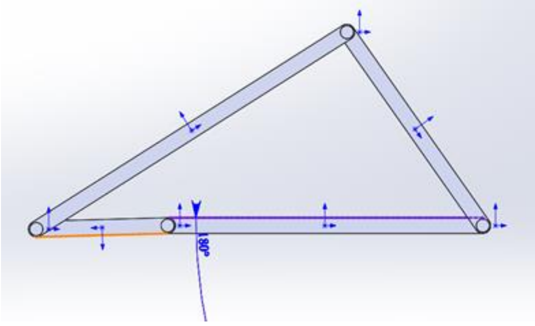
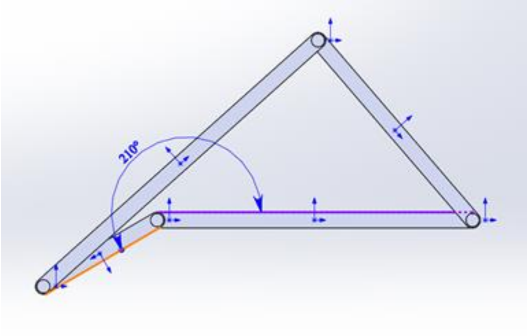
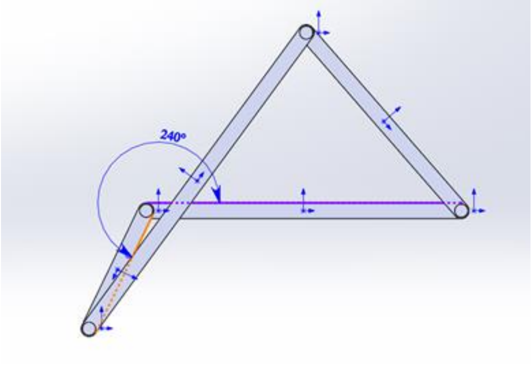
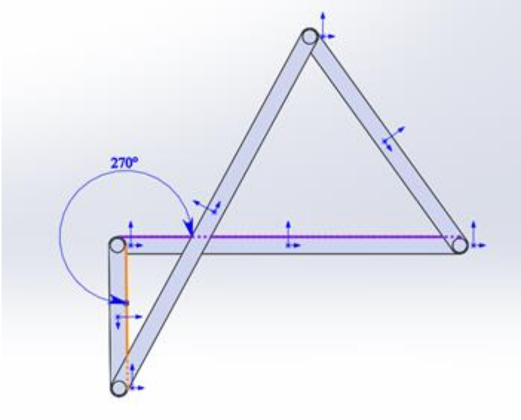
3.2.1 Illustrations of 4-bar mechanism motion

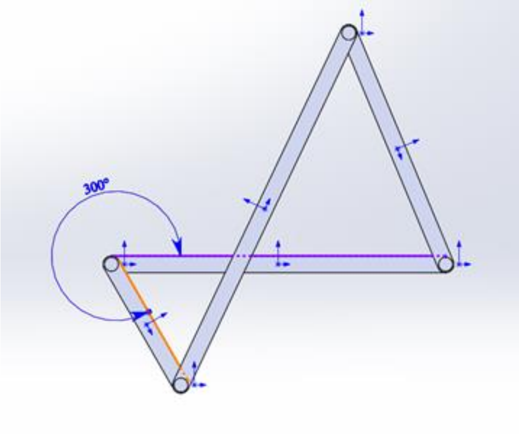
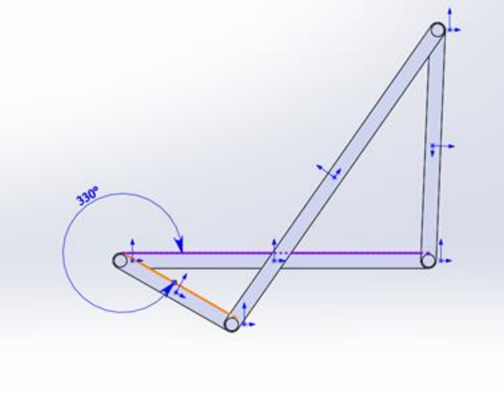
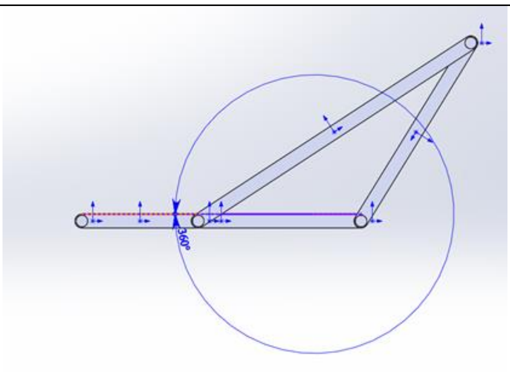
The following table illustrates the behaviour of our Crank-rocker mechanism, while the motion of θ_2 changes with step of 30^0.

Table 9. Change of our mechanism motion every 30^0 of angle θ_2

θ_2 angle, degrees	**θ_2 motion change**
0	
30	

θ_2 angle, degrees	θ_2 motion change
60	
90	
120	
150	

θ_2 angle, degrees	θ_2 motion change
180	
210	
240	
270	

θ_2 angle, degrees	θ_2 motion change
300	
330	
360	

3.2.2 Modelling

1) Our first step is creating 2D Sketch of Link1.

- Using operation Sketch we draw a parallelogram with length=63 mm, width=3 mm
- On the parallelogram we sketch two circles with the diameter of 2 mm. The distance between each side and center of circle is 1.5 mm.

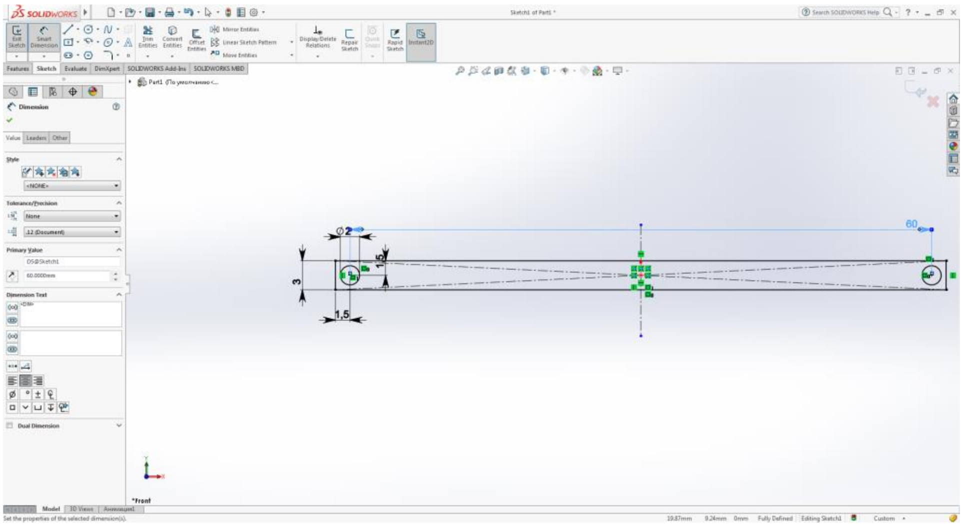


Figure 18. Sketch of Link1

2) Next step is:

- Exit Sketch
- Use operation Extruded Boss/Base with Sketch1 with the depth=1 mm

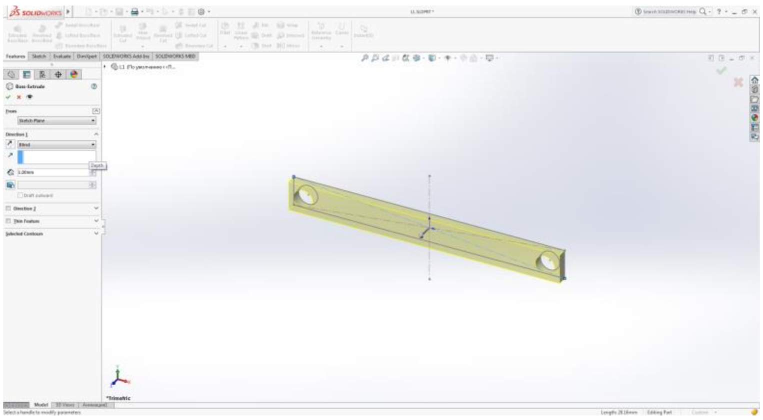
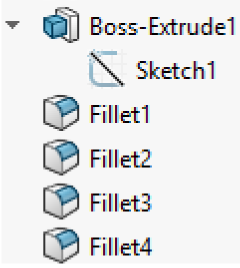


Figure 19. Link1, Extruded

3) After Extrusion we use operation Fillets to round off angles of the Link1.



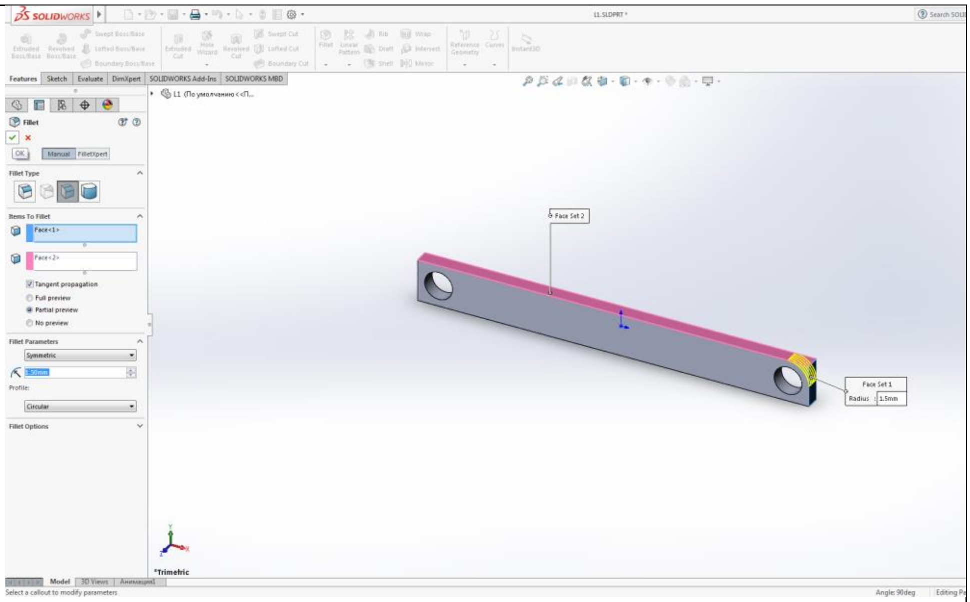


Figure 20. Fillets

4) As a result, we get first Link of our mechanism.

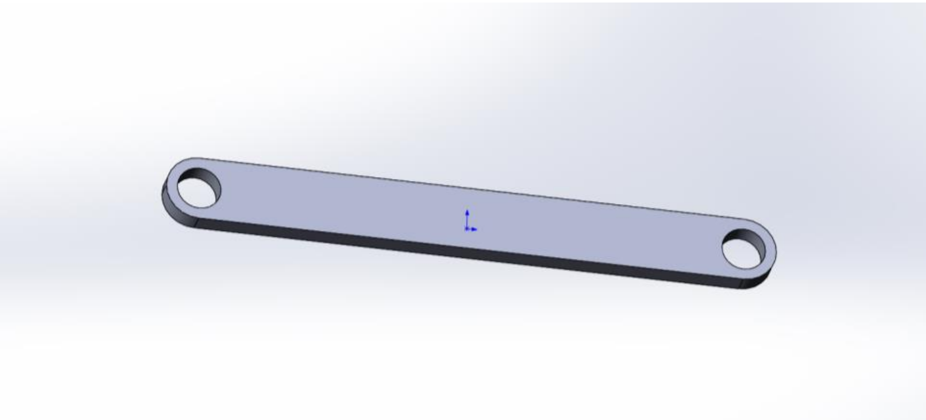


Figure 21. Ready part of Link1

5) Save as Link1.SLDPRT

6) Modelling of Link 2, Link 3 and Link 4:

- We open saved file Link1.SLDPRT
- Then we choose Edit Sketch operation
- Using operation Smart dimension, we change the distance between centers of circles to 25 mm for Link 2.
- Then we save our part as Link2.SLDPRT.

• For creating Link 3 we use the same previous operations with the distance equal to 70 mm and for Link 4 we use distance equal to 45 mm.

• Save files as Link3.SLDPRT and Link4.SLDPRT

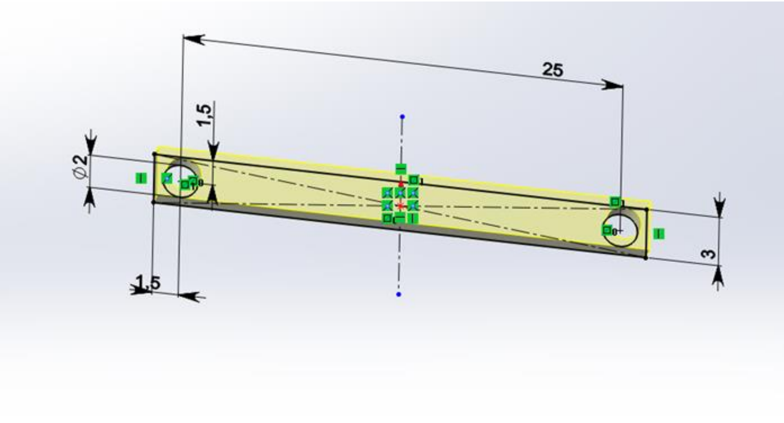


Figure 22. Modelling of Link2

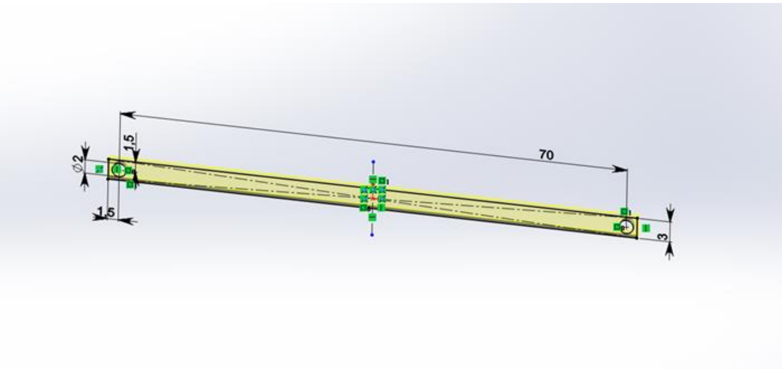


Figure 23. Modelling of Link3

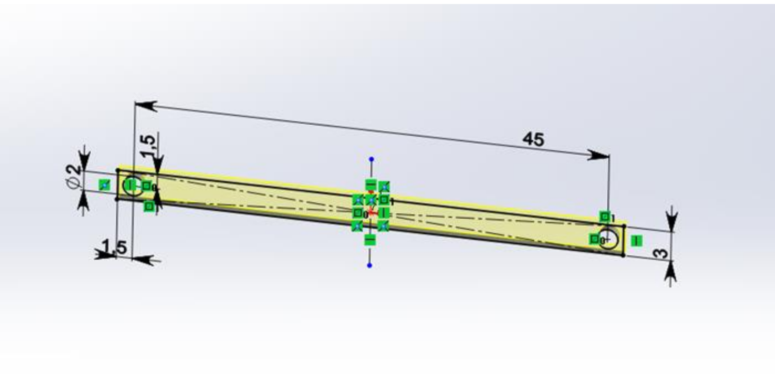
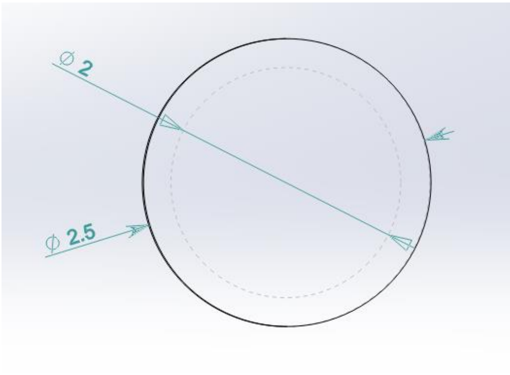
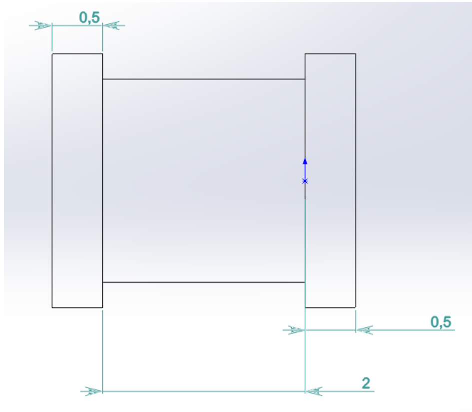


Figure 24. Modelling of Link4

7) Modelling a bolt to clamp together Parts in the final Assembly.

Table 10. Bolt dimensions





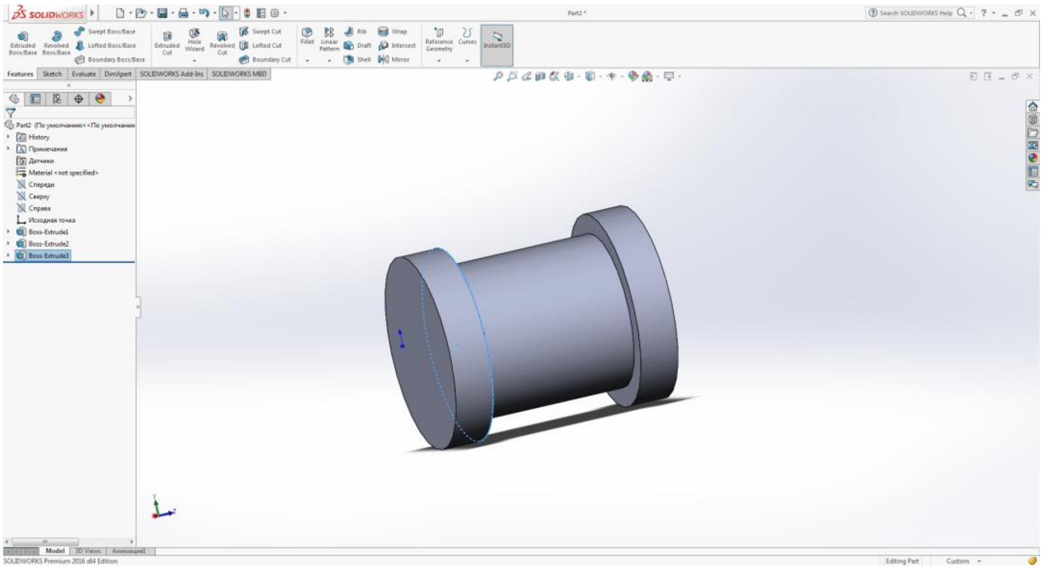


Figure 25. Bolt

8) Creating the Assembly

- We open New SolidWorks Document and choose Assembly.
- Then import our parts of Link 1-4 and Bolt.

- We connect parts with Mate operation. We choose surfaces of holes and bolt surfaces and use Concentric Mate. For connecting surfaces of Link bars, we use Coincident Mate command. See Figure 26, Figure 27, Figure 28, Figure 29, Figure 30.

Figure 26. Assembly command

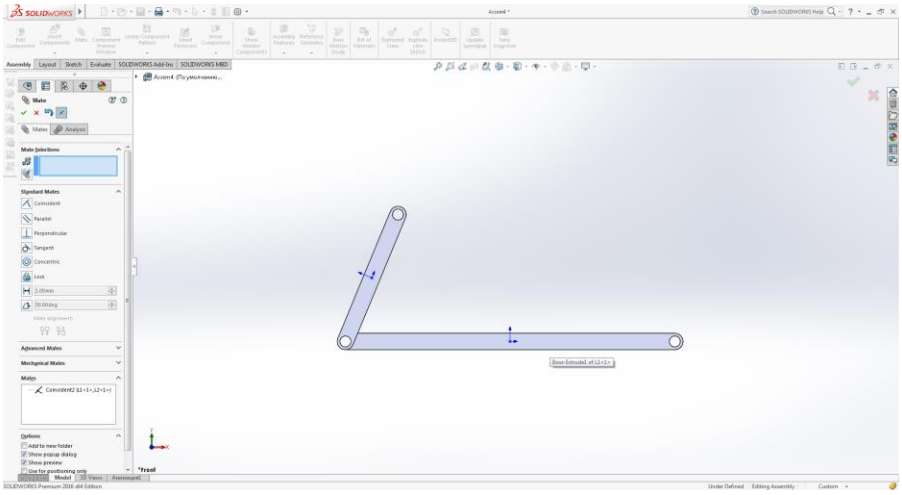


Figure 27. Mate command

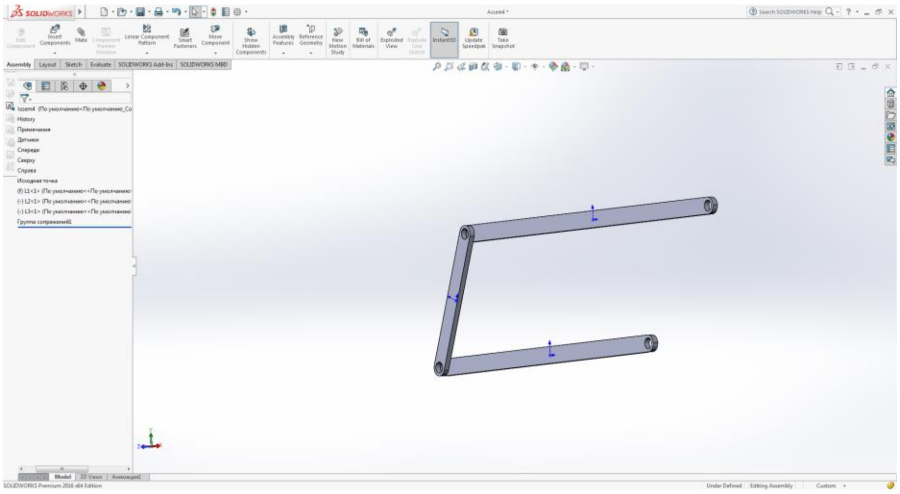


Figure 28. Assembly process

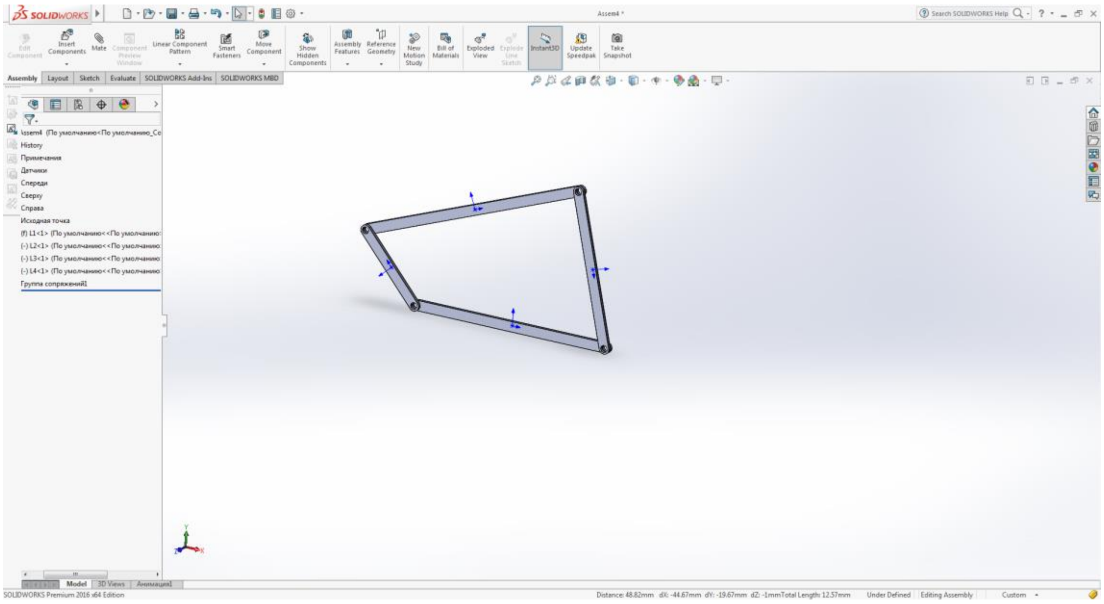


Figure 29. Link1-4 in one Assembly

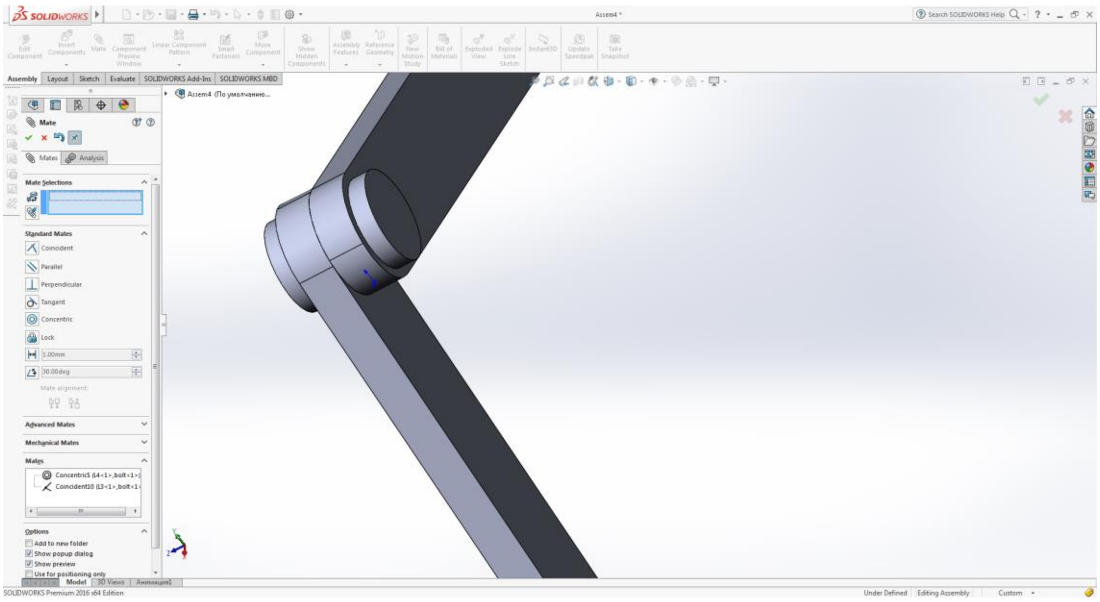


Figure 30. Bolt Mate

9) As a result, we get the Assembly of 4-bar mechanism, which we use in the following simulations.

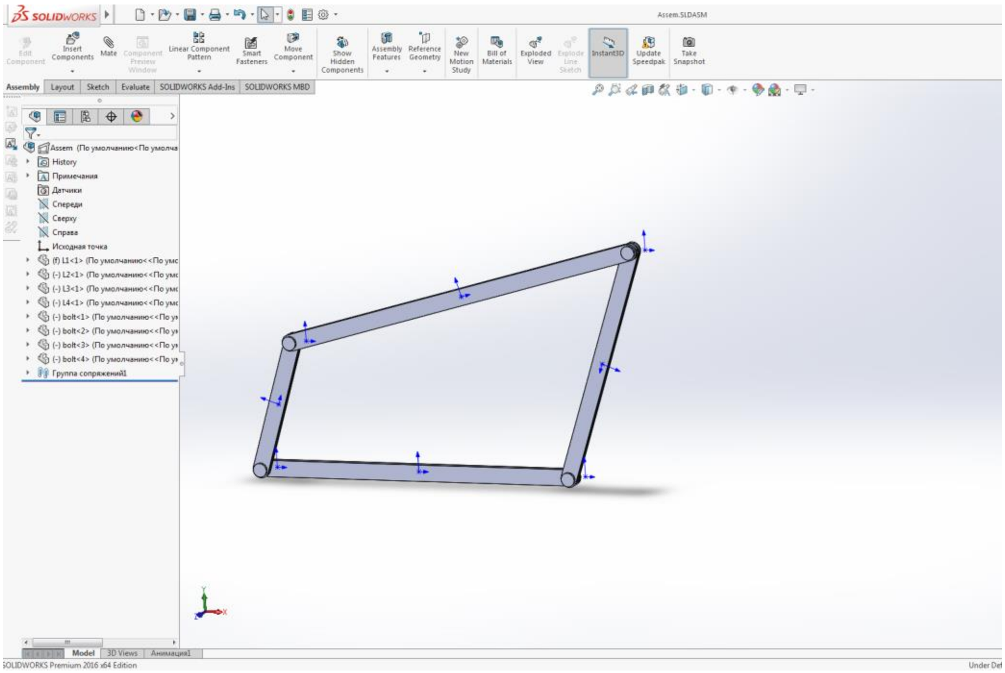


Figure 31. Final model of Assembly

3.2.2 Animation

10) For our next step – Animation command of our 4-bar mechanism.

- We use this command to show Crank-rockers motion.
- In Motor Type we choose "Rotary Motor" and set component of motor, which is Link1 and Set the direction.
- As Constant Speed we set value of 10 RPM and as time limit value is 6 seconds.

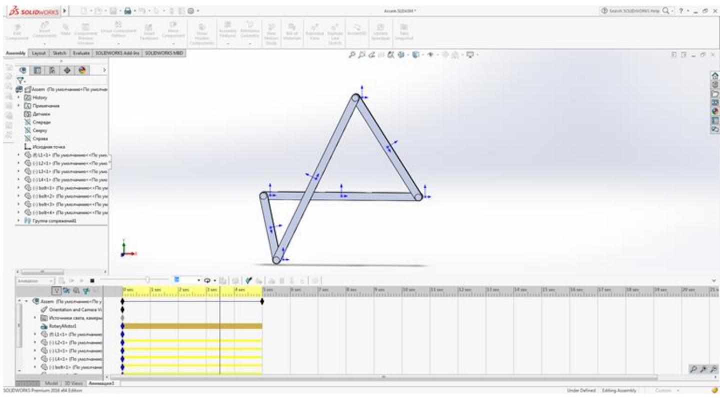


Figure 32. Behavior of Mechanism

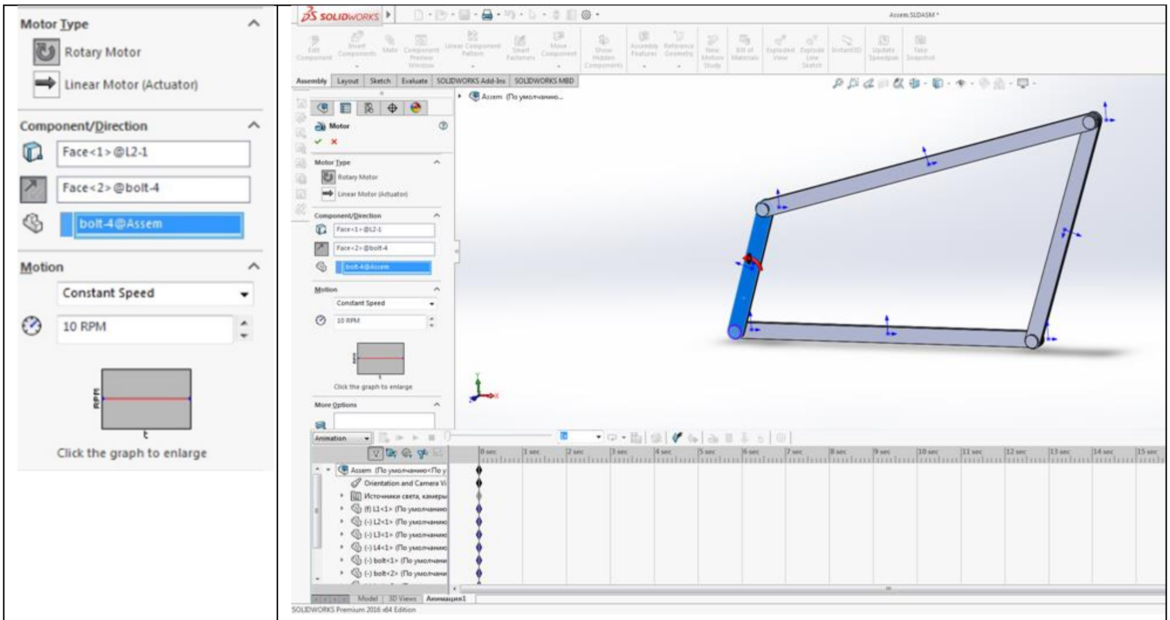


Figure 33.Animation simulation procedure

11) To Calculate the Velocities and Accelerations we use Motion Analysis

- We use “Calculate” operation and “Results and Plots” to obtain needed graphs
- In the “Results and Plots” we choose “Displacement/Velocity/Acceleration” Analysis.
- To start with, as sub-category we analyze Angular Displacement.

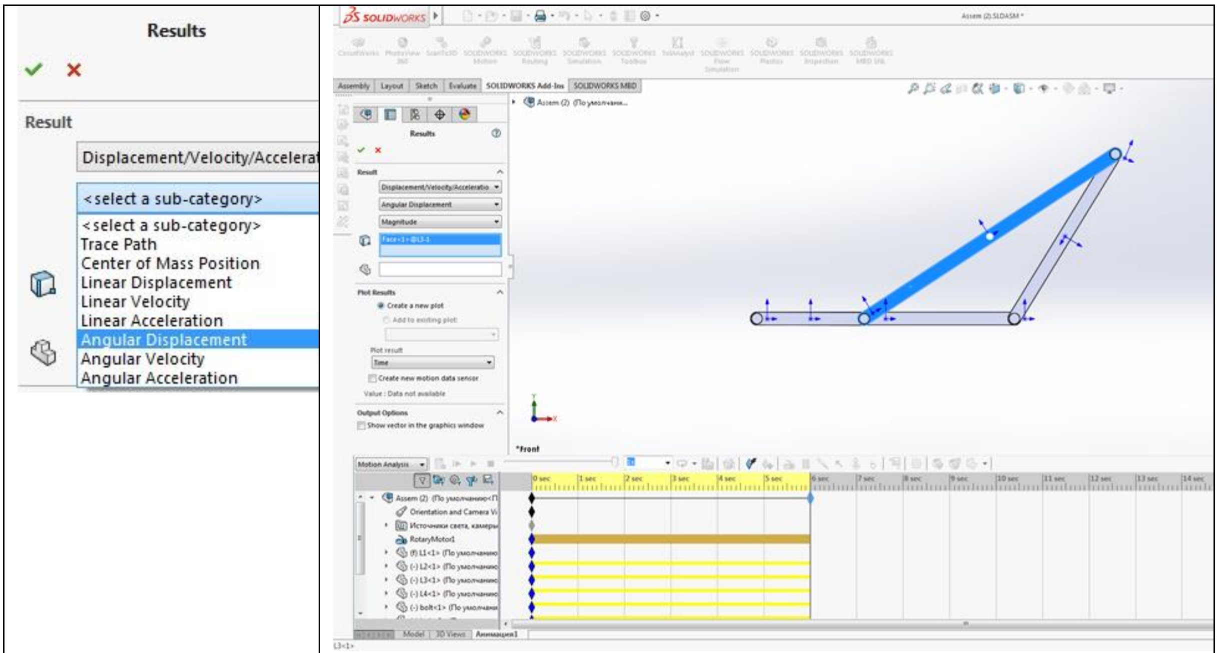


Figure 34. Motion analysis

12) As a result, we get:

- Graph1, showing the behavior of θ_3
- Graph2 Showing the behavior of θ_4

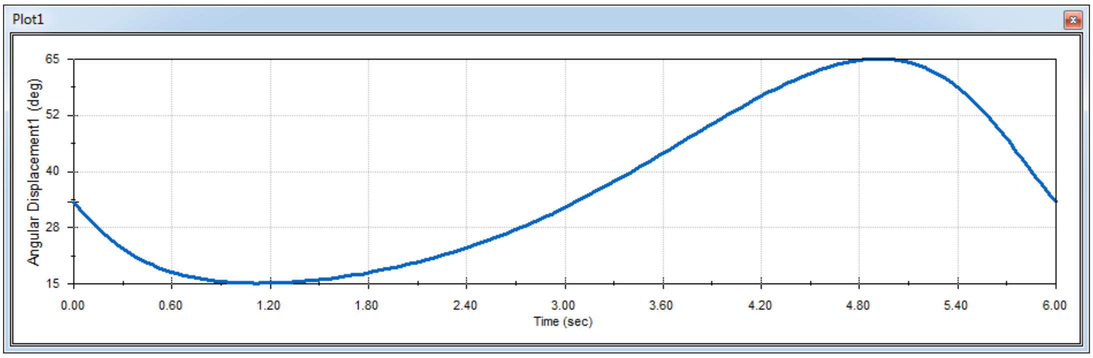


Figure 35. Graph1 – angular displacement

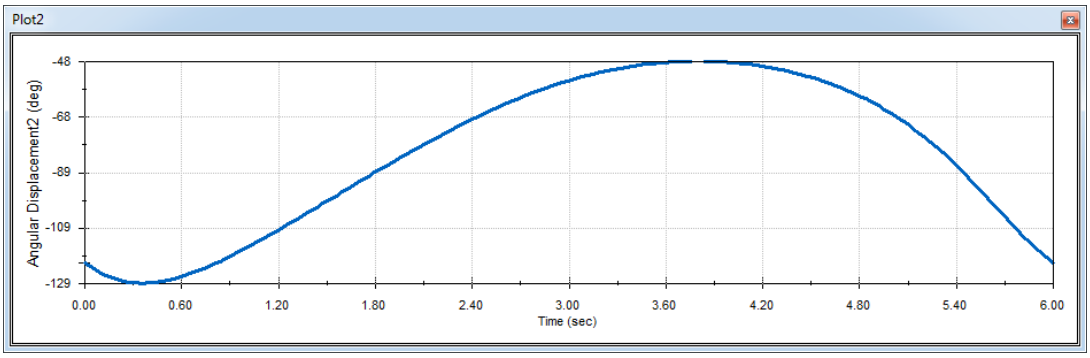


Figure 36. Graph2 – angular displacement

13) The same method, described in the 12^{th} paragraph, we are using to analyze Angular Velocities and Angular Accelerations.

- The Angular Velocities Graphs3 and Graph 4:

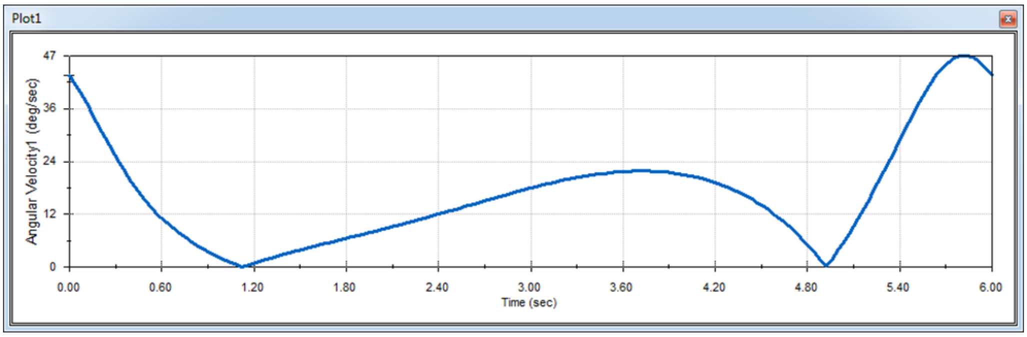


Figure 37. Graph 3 – angular velocity

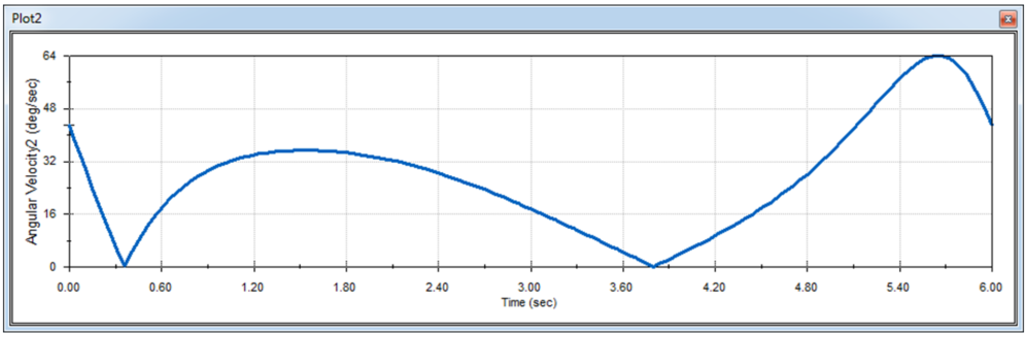


Figure 38. Graph 4 – angular velocity

- The Angular Accelerations Graph 5 and Graph 6:

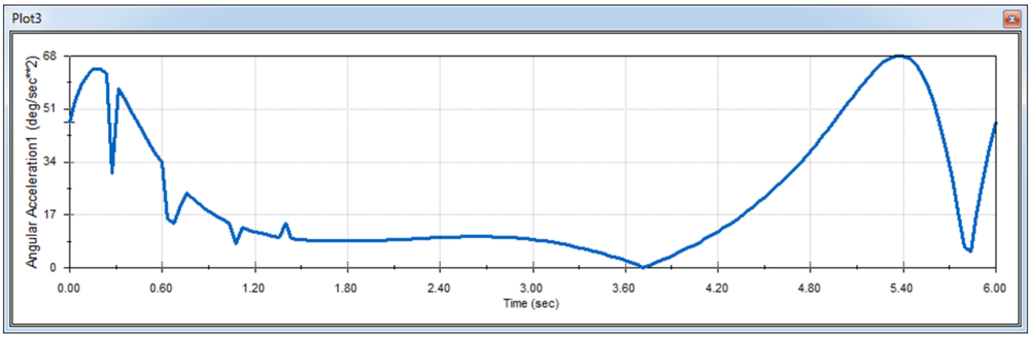


Figure 39. Graph 5 – angular acceleration

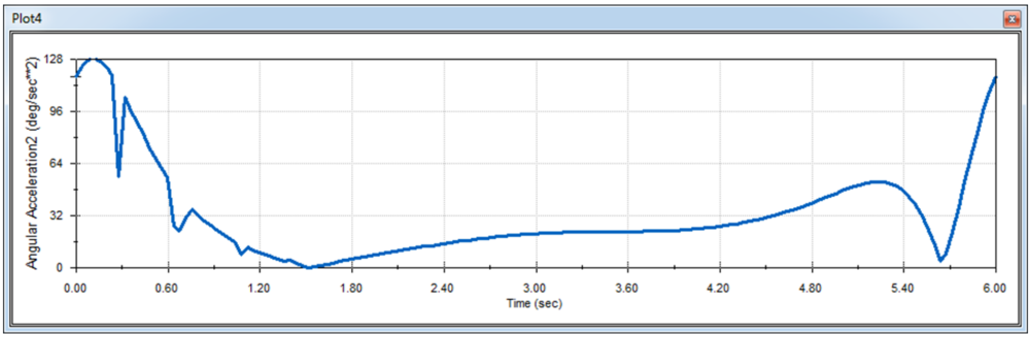


Figure 40. Graph 6 – angular acceleration

4. RESULTS

As a result, we obtained the graphics and mathematical data from theoretical Excel calculations and SolidWorks Simulations to compare.

4.2 Theoretical results obtained via Excel.

The following chapter represents collected angle displacement, angular velocities and angular accelerations values with using Microsoft Excel in the Table 11. On the base of obtained values, we got graphics of angle displacement, angular velocities and angular accelerations behavior, illustrated in **Error! Reference source not found.**.

4.2.1 Mathematical data

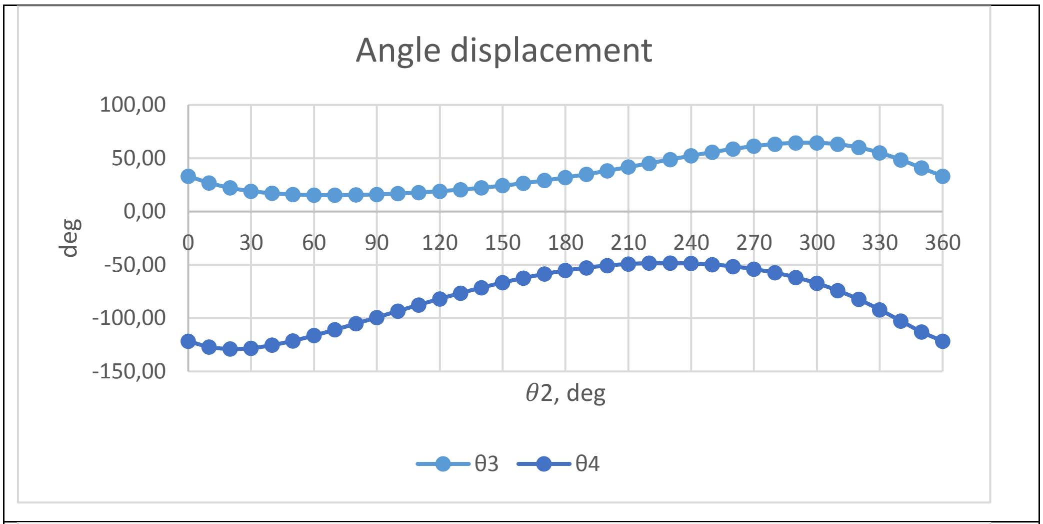
Table 11. Obtained Excel data

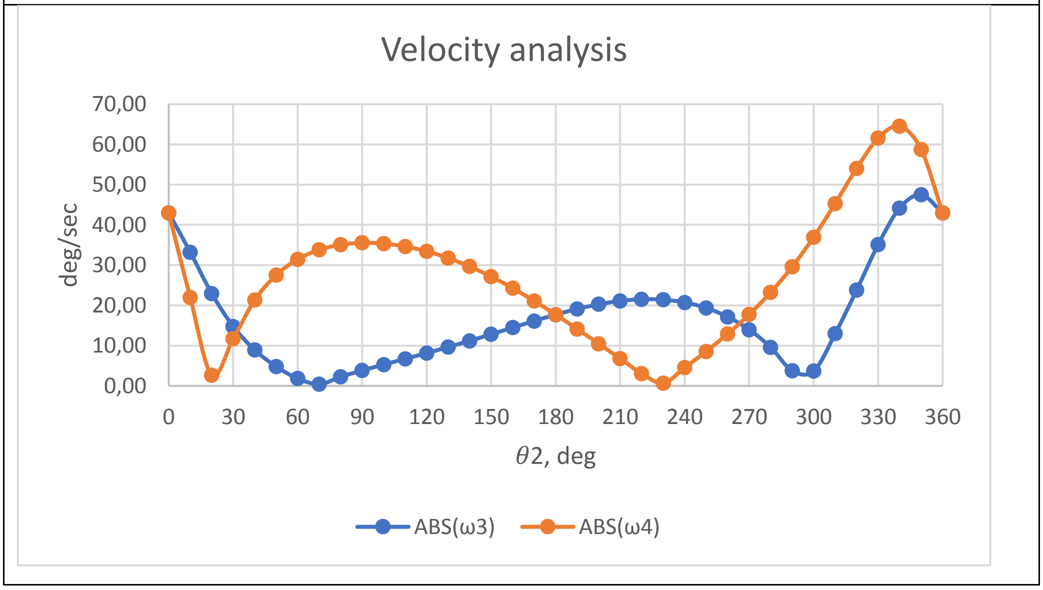
Angle, θ_2, deg	**Angle, θ_3, deg**	**Angle, θ_4, deg (inner)**	**ABS, angular velocity (ω_3), deg/sec**	**ABS, angular velocity, (ω_4), deg/sec**	**ABS, angular acceleration, (α_3), deg/s^2**	**ABS, angular acceleration, (α_4), deg/s^2**
0	33,20	-121,59	42,86	42,86	47,31	117,56
30	19,08	-128,16	14,73	11,67	41,56	68,35
60	15,48	-116,33	1,84	31,36	15,29	33,46
90	16,10	-99,28	3,82	35,45	9,03	11,03
120	19,09	-81,89	8,14	33,34	8,73	5,12
150	24,30	-66,63	12,79	27,07	9,83	15,98
180	31,93	-55,35	17,65	17,65	9,02	20,94
210	41,71	-49,22	21,05	6,77	3,81	22,27
240	52,35	-48,63	20,68	4,52	6,09	24,86
270	61,34	-54,04	13,93	17,69	22,39	29,68

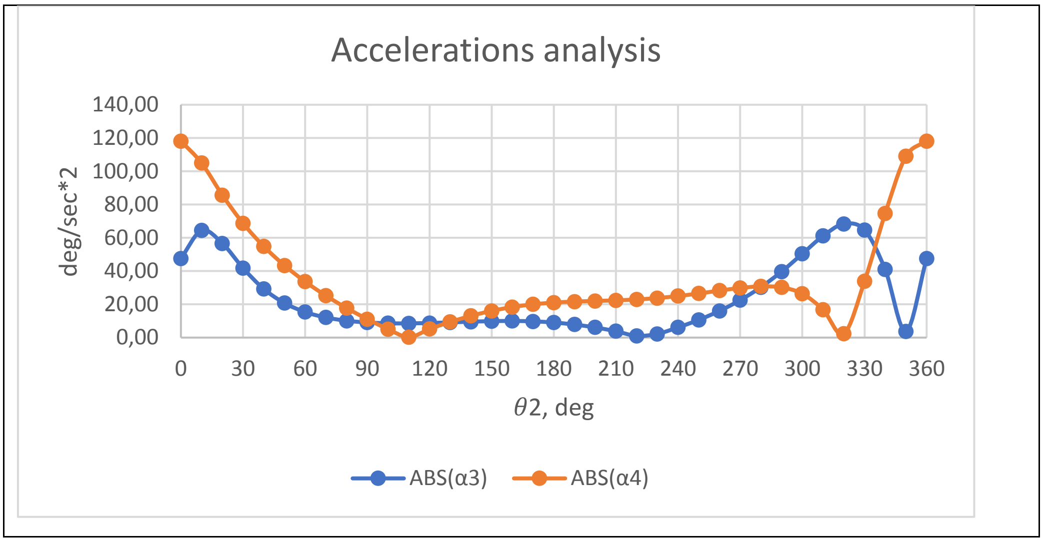
Angle, θ_2, deg	Angle, θ_3, deg	Angle, θ_4, deg (inner)	ABS, angular velocity (ω_3), deg/sec	ABS, angular velocity, (ω_4), deg/sec	ABS, angular acceleration, (α_3), deg/s^2	ABS, angular acceleration, (α_4), deg/s^2
300	64,48	-67,33	3,67	36,86	50,11	26,24
330	55,19	-92,06	34,99	61,39	64,37	33,63
360	33,20	-121,59	42,86	42,86	47,31	117,56

4.2.2 Graphics

Table 12. Obtained Excel graphics







4.3 SolidWorks results

The following chapter represents collected angle displacement, angular velocities and angular accelerations values with using SolidWorks software (see Figure 41, Figure 42, Figure 43). On the base of obtained values, we got graphics of angle displacement, angular velocities and angular accelerations behavior, illustrated in Figure 44, Figure 45, Figure 46.

4.3.1 Mathematical data

As we have $\omega_2 = 10$ [rpm], as default angular speed, it means that Link2 changes position every 30^0 in 0.5 seconds step. Therefore, obtained angular velocities and accelerations data remains suitable for following comparability with Excel collected values.

Frame	Time	L3-1 Angular Displacement1 (deg) Ref. Coordinate System:	L4-1 Angular Displacement2 (deg) Ref. Coordinate System:
1	0,0	33,28	-121,51
11	0,5	19,11	-128,18
21	1,0	15,48	-116,39
31	1,5	16,09	-99,34
41	2,0	19,08	-81,94
51	2,5	24,28	-66,67
61	3,0	31,89	-55,38
71	3,5	41,67	-49,23
81	4,0	52,31	-48,62
91	4,5	61,32	-54,01
101	5,0	64,49	-67,26
111	5,5	55,25	-91,95
121	6,0	33,28	-121,51

Figure 41. Obtained SolidWorks data of displacements behaviour

Frame	Time	L3-1 Angular Velocity1 (deg/sec) Ref. Coordinate System:	L4-1 Angular Velocity2 (deg/sec) Ref. Coordinate System:
1	0,0	42,94	43,06
11	0,5	14,83	11,51
21	1,0	1,86	31,33
31	1,5	3,77	35,44
41	2,0	8,12	33,36
51	2,5	12,77	27,10
61	3,0	17,63	17,69
71	3,5	21,05	6,80
81	4,0	20,69	4,48
91	4,5	13,97	17,64
101	5,0	3,55	36,76
111	5,5	34,87	61,33
121	6,0	42,94	43,06

Figure 42. Obtained SolidWorks data of velocities behaviour

Frame	Time	L3-1 Angular Acceleration2 (deg/sec**2) Ref. Coordinate System:	L4-1 Angular Acceleration3 (deg/sec**2) Ref. Coordinate System:
1	0,0	46,97	117,22
11	0,5	41,80	71,02
21	1,0	15,34	18,26
31	1,5	9,08	1,01
41	2,0	8,73	8,63
51	2,5	9,83	16,12
61	3,0	9,03	20,92
71	3,5	3,84	22,16
81	4,0	6,04	23,47
91	4,5	22,31	30,62
101	5,0	49,92	47,14
111	5,5	64,50	35,67
121	6,0	46,97	117,22

Figure 43. Obtained SolidWorks data of accelerations behaviour

4.3.2 Graphics

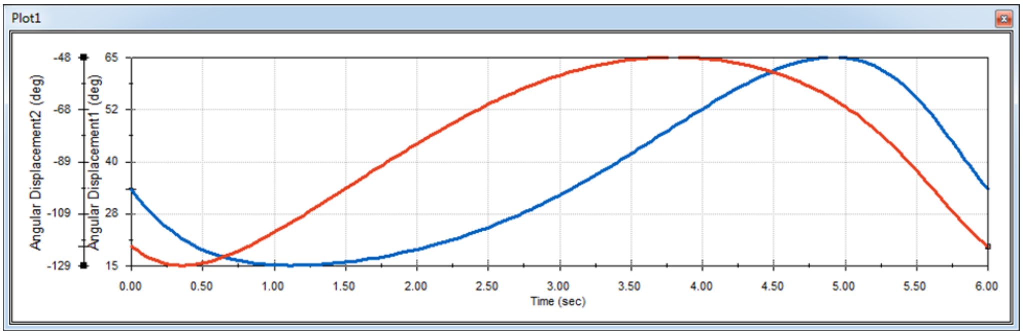


Figure 44. Obtained SolidWorks graphs of displacements behaviour

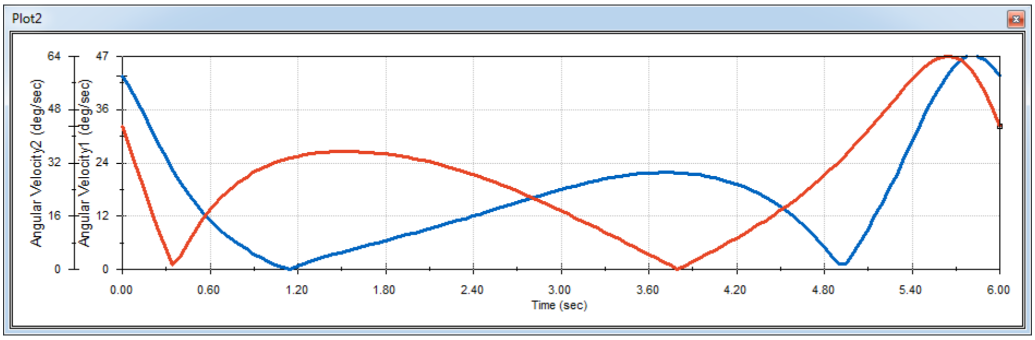


Figure 45. Obtained SolidWorks graphs of velocities behaviour

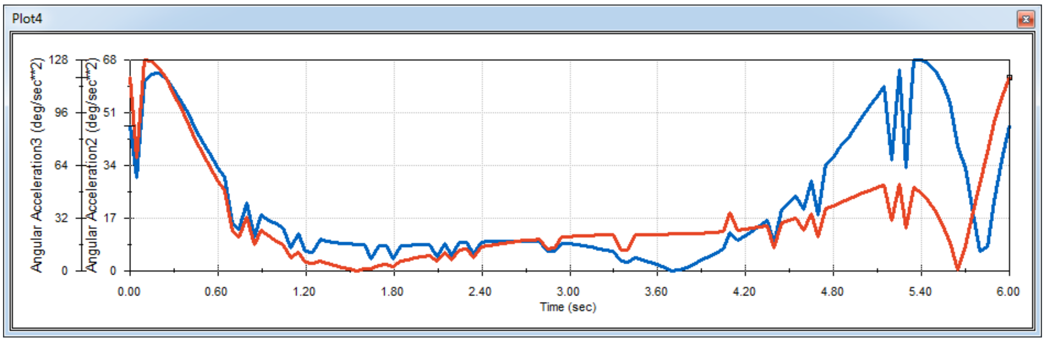


Figure 46. Obtained SolidWorks graphs of accelerations behaviour

4.3.3 Percentage error for the angles

To calculate the angle values accurately, the percentage error has to be performed. We use the following formula:

$$\%\,Error = \left(\frac{Theoretical\ value - Experimental\ value}{Theoretical\ value}\right) \cdot 100\ ,$$

Where:

- Theoretical value is defined as Excel data.
- Experimental value is data, obtained by SolidWorks.

As a result, the percentage error for θ_3 and θ_4 is presented in Table 13.

Table 13. Percentage error of angles

% Error		**Theoretical value (Excel), deg**		**Experimental value (SolidWorks), deg**	
$\boldsymbol{\theta_3}$	$\boldsymbol{\theta_4}$	**θ3**	**θ4**	**θ3**	**θ4**
0,24	0,07	33,2	-121,59	33,28	-121,51
0,16	0,02	19,08	-128,16	19,11	-128,18
0,00	0,05	15,48	-116,33	15,48	-116,39
0,06	0,06	16,1	-99,28	16,09	-99,34
0,05	0,06	19,09	-81,89	19,08	-81,94
0,08	0,06	24,3	-66,63	24,28	-66,67
0,13	0,05	31,93	-55,35	31,89	-55,38
0,10	0,02	41,71	-49,22	41,67	-49,23
0,08	0,02	52,35	-48,63	52,31	-48,62
0,03	0,06	61,34	-54,04	61,32	-54,01
0,02	0,10	64,48	-67,33	64,49	-67,26
0,11	0,12	55,19	-92,06	55,25	-91,95
0,24	0,07	33,2	-121,59	33,28	-121,51

4.4 Excel and SolidWorks comparison

During the Analyzing of Crank-Rocker Mechanisms using Theory and SolidWorks software, we obtained approximately equal results. It is observed with the graphics and mathematical data, received during Excel Analysis and SolidWorks Motion Simulation.

By the Graphics observation, it is determined that the motion behavior of angular displacements, angular velocities and angular accelerations is approximately identical.

The following table (Table 14) shows the summarized collected mathematical data, using theoretical calculations and SolidWorks Simulation. Mostly all data, obtained from Excel and SolidWorks, is similar.

In addition, there was calculated percentage error of angle values, obtained by SolidWorks.

Table 14. Summarised obtained data

Theoretical calculations values							SolidWorks simulation data							% Error of angles	
Angle, θ_2, deg	**Angle, θ_3, deg**	**Angle, θ_4, deg (inner)**	**ABS, ang. velocity, (ω_3), deg/sec**	**ABS, ang. velocity (ω_4), deg/sec**	**ABS, ang. acceleration, (α_3), deg/s^2**	**ABS, ang. acceleration, (α_4), deg/s^2**	**Angle, θ_2, deg**	**Angle, θ_3, deg**	**Angle, θ_4, deg**	**Ang. velocity, (ω_3), deg/sec**	**Ang. velocity, (ω_4), deg/sec**	**Ang. acceleration, (α_3), deg/s^2**	**Ang. acceleration, (α_4), deg/s^2**	θ_3	θ_4
0	33,20	-121,59	42,86	42,86	47,31	117,56	0	33,28	-121,51	42,94	43,06	46,97	117,22	0,24	0,07
30	19,08	-128,16	14,73	11,67	41,56	68,35	30	19,11	-128,18	14,83	11,51	41,80	71,02	0,16	0,02
60	15,48	-116,33	1,84	31,36	15,29	33,46	60	15,48	-116,39	1,86	31,33	15,34	18,26	0,00	0,05
90	16,10	-99,28	3,82	35,45	9,03	11,03	90	16,09	-99,34	3,77	35,44	9,08	1,01	0,06	0,06
120	19,09	-81,89	8,14	33,34	8,73	5,12	120	19,08	-81,94	8,12	33,36	8,73	8,63	0,05	0,06
150	24,30	-66,63	12,79	27,07	9,83	15,98	150	24,28	-66,67	12,77	27,10	9,83	16,12	0,08	0,06
180	31,93	-55,35	17,65	17,65	9,02	20,94	180	31,89	-55,38	17,63	17,69	9,03	20,92	0,13	0,05
210	41,71	-49,22	21,05	6,77	3,81	22,27	210	41,67	-49,23	21,05	6,80	3,84	22,16	0,10	0,02
240	52,35	-48,63	20,68	4,52	6,09	24,86	240	52,31	-48,62	20,69	4,48	6,04	23,47	0,08	0,02
270	61,34	-54,04	13,93	17,69	22,39	29,68	270	61,32	-54,01	13,97	17,64	22,31	30,62	0,03	0,06
300	64,48	-67,33	3,67	36,86	50,11	26,24	300	64,49	-67,26	3,55	36,76	49,92	47,14	0,02	0,10
330	55,19	-92,06	34,99	61,39	64,37	33,63	330	55,25	-91,95	34,87	61,33	64,50	35,67	0,11	0,12
360	33,20	-121,59	42,86	42,86	47,31	117,56	360	33,28	-121,51	42,94	43,06	46,97	117,22	0,24	0,07

5. DISCUSSION

During writing this thesis, important problems occurred, which prevented in some additional ideas.

For example, there was planned study of real case example. But the SolidWorks software demanded additional knowledge to design such a model, that would not give mistakes in Simulation. Considering the lack of time, this idea had been cancelled.

Because of the same reason, there was change in mechanism type designing. The crank-rocker mechanism was chosen, as it is more applicable for thesis objectives to be completed.

In following studies, it would be recommended to solve appeared problem with SolidWorks Simulation mistakes.

Supplementary, in chapter “4.3.3 Percentage error for the angles” there were presented calculations of percentage error of angles θ_3 and θ_4, collected with SolidWorks only, due to the fact, that theoretical values calculated in Excel, are assumed to be utmost correct. SolidWorks percentage error data is considered to be accurate also.

6. CONCLUSION

The basic idea of this thesis is design a 4-bar mechanism, which is analyzed, using theoretical concepts of mechanisms and SolidWorks Simulation to compare the obtained values. As it is clearly seen through Results chapter, the major objectives have been achieved.

Firstly, the basic concepts of Crank-rocker mechanism were studied. Afterwards, the required values of angular velocities and accelerations were obtained – theoretical calculations and Microsoft Excel were used. The working model of 4-bar mechanism was designed and simulated in SolidWorks Motion to obtain graphs and data. Consequently, collected results present that theoretical and SolidWorks data have coincidental parameters, which slightly differs. It indicated, that SolidWorks Software is advisable platform for following researches in this field.

It is recommended to study further the SolidWorks software to analyze the real-life example, which creation had not been succeeded in this thesis. In addition, by completing the modelling the mechanism of real-life case, there could be done production of mechanism by 3-D printer. In that case, there mechanism concept should be researched more deeply and, therefore, the practicable application for that type of mechanism should be developed.

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