Examples of kinematic analysis of complex mechanism using modern software applications

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Abstract. Analysis of planar or spatial mechanisms as segments of real complex systems and machines in the domain of kinematics, kinetostatic, dynamic, functional and other aspects of analysis can be done by analytical methods and by applying contemporary software applications. This paper shows some examples of complex mechanism analysis using SolidWorks software, which provides a special module for quick analysis with a visual representation of characteristic data mechanism for different members position as a diagrammatic representation of certain parameters throughout the observed motion cycle. Such representations are very useful in designing mechanisms in the manner of analysis or synthesis. Analysis of characteristic points of moving members of the mechanism with the presentation of its path during the motion cycle, the analysis of velocity and acceleration vectors of members’ moving points, forces on the members of the mechanism, definition of the moment or force on the drive member of the mechanism, the path of the executive member of the mechanism, the possibility of collision in the movement of the members of the mechanism, the geometry of the members of the mechanism based on the required path of the movement of the executive member of the mechanism, etc., are only some of the possible areas of analysis.

1. Introduction
Realistic machine systems and devices for manufacturing, transportation, service and many other uses are mostly complex planar or spatial type mechanisms that incorporate a number of kinematic-bound elements that have a drive, transfer, or executive character in performing a complex task. These include, for example, lifting and lowering systems for aeroplane wheels and cargo platforms, machine mechanisms for sorting large quantities of small miscellaneous products, mechanisms for opening and closing the door of the lifts, mechanisms for movement and securing the force at the production machinery of various uses, mechanisms of robotic complex systems, operating and executive elements of construction machinery, etc.

In the process of analyzing existing solutions for optimization and improvement, or in the process of creating new conceptual solutions of complex mechanisms, the kinematic analysis of characteristic points of executive members of the mechanism, the analysis of the motion of moving points, the analysis of the driving forces or forces on the executive and other members are some of the important segments, where the use of an analytical approach to a vector calculations, the application of analysis by the relative velocity and acceleration method, the use of the current centres method, etc., are very significant, [1,2,3].
Certainly, contemporary software solutions for different purposes, including these, derive from the needs of the real industry for the purpose of realizing reliable and rapid analyzes, and in order to create optimal solutions, according to the default goal function.

This paper will present examples of application of software and its modules for kinematic analysis of mechanisms that provide a quick analysis with visual representation of characteristic data for the positions of one or more members of the mechanism or for the overall cycle of the movement of the mechanism.

When applying software solutions, the basis of the overall analysis is to create a 2D or 3D model of all the components of the mechanism, then connect the component kinematic links that limit the movement, or reduce the number of degrees of freedom of the mechanism. The degree of model approximation to the actual situation is higher in more demanding systems than in a simpler software, which increases hardware requirements. Certainly, the creation of members of the mechanism in terms of geometric characteristics, the type of connection between them, and the assignment of driving characteristics to one of the members of the mechanism are features that have a crucial effect on the overall performance of the overall mechanism and its functionality.

Certainly, after kinematic analysis, for realistic systems it is necessary to carry out kinetostatic and dynamic analysis, especially in those where speeds, accelerations and masses of system members are significant, as well as in a system that exerts significant forces on executive and transmitting members, e.g. in manufacturing machines for deformation technology, etc.

Benefits of using software packages, among others, include: visualization of the movement of the mechanism in the virtual environment with all the details, quick data processing and obtaining output data for various input parameter combinations, the ability to use output data for different applications, and the possibility of direct transfer to dynamic analysis.

2. Examples of some software solutions for complex mechanism analysis

There are various softwares that allow for the creation and analysis of complex mechanisms, as well as very detailed analysis of all member movements in characteristic points, individual positions of the mechanism members, or for total movement cycles. Some of them are: SolidWorks, MechDesigner, SAM - the ultimate mechanism designer, Linkage, Pro/Engineer, etc., [1, 4, 7].

2.1. Linkage - mechanism designer and simulator

It is a computer program that allows the user to create and edit planar-based mechanisms and simulate their movement. This program cannot perform detailed motion analyzes, such as determining velocity and acceleration of individual members of the mechanism, but is extremely useful in cases where it is necessary to see how each member of the mechanism is connected and what their mutual mobility is. By entering different input parameters and relationships between members, it is possible to determine the function of movement and make appropriate changes to improve the functioning of the mechanism itself. Also, in this way, it is easy to check whether the dimensions and path of the mechanism are obtained by analytical or graphical method properly defined. Figure 1 shows Whitworth's mechanism with drawn paths of selected moving points. If there is a fault in the design of the mechanism or dimensions, e.g. if the length of the sliding path is not long enough and the slider will slip out of it, the program will report an error, stop with the simulation of the motion, and display the location on the mechanism where irregularities occur.

Once the members of the mechanism have been formed, it is necessary to define the driving members, as well as the input parameters such as the speed of the drive member, and the dimension of individual members.
2.2. SAM – the ultimate mechanism design software
The SAM software solution allows the design, analysis and optimization of planar mechanisms. The way of assembling the mechanism is very easy using basic components such as beams, sliders, gears, springs, absorbers and friction elements. This program integrates preprocessing, numerical analysis and postprocessing, which involves creating animations and xy-diagrams in a simple to use environment.

DXF import / export option allows the translation of the created concept of mechanism into any CAD program for further editing and analysis, as well as entering CAD data, for simple editing or animation of the final mechanism.

When the mechanism is created and input parameters defined, it is possible to calculate any kinematic size including the member position, shift, velocity, acceleration, angles, angles of velocity and acceleration, figure 2. Additionally, the SAM program also provides dynamic analysis.

![Figure 1. View of the path of selected points of the Whitworth mechanism.](image1)

![Figure 2. Some of Whitworth's mechanism analysis results display: a) Tabular display of velocity and acceleration results; b) Display of the speed of the selected points.](image2)
2.3. SolidWorks
SolidWorks is 3D CAD (Computer Aided Design) and CAE (Computer Aided Engineering), a Dassault Systèmes program. According to statistics of companies that commercially offer this software, this program currently utilizes over 2 million engineers and designers, and more than 165,000 companies around the world. SolidWorks uses the principle of 'solid modelling' and parameter access to model design and 'assembly' options for complex systems. The software is written on the Parasolid kernel.

SolidWorks in options of SolidWorks Standard, Premium, and Professional configuration software contains a significant number of modules for the corresponding tasks:
- Engineering Data Management: SolidWorks Enterprise PDM,
- Engineering calculations: SolidWorks Simulation Professional, SolidWorks Simulation Premium, SolidWorks Flow Simulation,
- Electrical design: SolidWorks Electrical,
- Creating an internet documentation: SolidWorks Composer,
- Machining, CNC: CAMWorks,
- System Check: CAMWorks Virtual Machine,
- Quality control: SolidWorks Inspection,
- Technology Analysis: SolidWorks Plastics, DFM, etc.,
- E-drawing Technologies: SolidWorks MBD (Model-Based Definition).

For the purpose of creating and analyzing examples from domain of mechanisms, the subforms for the creation of 3D models and SolidWorks Motion are the most commonly used.

3. Example of complex systems analysis in the SolidWorks software solution
Through this section, over selected example of the planar complex mechanism, the application of kinematic analysis of the complex mechanisms in SolidWorks software will be shown.

Firstly a 3D model (Module Assembly) must be created. In addition to the use of 3D models, kinematic or dynamic analysis of planar mechanisms, it is important to note that in the case of the use of the Motion Analysis module, a 2D drawing of the mechanism can also be used. After the creation of the mechanism assembly with the geometrical characteristics of all members of the mechanism, the supports and the interconnections of individual members, a module for the analysis of movement of the mechanism during the multi-cycle motion processes or for certain parts of particular interest can be used. Solving tasks from the domain of kinematics mechanisms depends on the geometrical parameters of the members of the mechanism, the relation between the members and the boundary conditions of the supports and movements, as well as the initial driving parameters of one of the members of the mechanism.

SolidWorks Motion can also take into account other effects because, apart from the option to add driving motors, there are options for adding other modules such as:
- Spring (definition of spring together with stiffness coefficient),
- Damper,
- Force (definition of force acting together with intensity and place of action),
- Contact (definition of contact between two surfaces with definition of friction and type of material in contact),
- Gravity (adding gravity to the whole mechanism).

After establishing calculation of motion kinematic parameters of the mechanism, structural analysis can be performed due to the force induced by motion dynamics (acceleration and force in the bonds) or external acting forces on the members of the mechanism. After the calculation of the movement of the mechanism, it is possible to obtain time-based motion diagrams, trajectory of characteristic moving points of the members of the mechanism, speed vectors and accelerations for characteristic points, using the „Results and Plots“ option.
3.1. An example of a complex planar mechanism analysis

Figure 3a) shows a 3D model of examples with all the geometry parameters of the mechanism members, and Figure 3b) shows an example of using the 'Trace Path' option to obtain the path of the required moving points of the mechanism, [5, 6, 7].

Figure 3. Planar mechanism with all members: a) 3D view of the model, b) Display of trajectory of characteristic mechanism points using the 'Trace Path' option.

Figure 4 shows the speed change diagrams for the B and C points of mechanism in the time domain.

Figure 4. Speed change diagrams for individual points of mechanism in the time domain.

Figure 5 shows the acceleration diagrams for the B and C points with the ability to display the normal and tangential components of acceleration of the moving points of the mechanism.

Figure 5. Change of acceleration for individual points of mechanism in the time domain with views of normal and tangential acceleration components.
Also, it is possible to create velocity and acceleration vectors that automatically change the size and direction according to the current position value in an appropriate simulation. Figure 6 shows two selected positions from the total cycle of movement of mechanism members.

Figure 6. Two characteristic positions of the mechanism with speed and acceleration vectors.

4. Conclusions
The example presented shows the importance of possible analysis through the associated diagrams, the most important of which are the path diagrams with respect to the motion requirements of the individual points of the mechanism, and the speed and acceleration diagrams with special emphasis on the sudden changes in the speed values giving maximum acceleration, which are important for the dynamic mechanism stability. This reflects the scientific and practical application of the implemented software application methodology. In the case of analysis of mechanisms as parts of real devices or machines, such as: maximum mechanism member position, maximum speed or acceleration, motion point path, collision detection and real conduct of mechanism members motion, as well as creating an executive member of the mechanism according to the precisely defined motion curve for synthesis of mechanisms, etc. are just some essential segments that require a good understanding of vector calculation and application of software solutions.

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