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Multibody systems with closed structure: Dynamic analysis and visualization of slider crank mechanism

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ABSTRACT
Analysis of multibody system's behaviour with closed kinematic structure is subject of investigation in the paper. The basic idea of the paper is to develop the dynamic and virtual models of this kind of multibody systems and establish two-way communication between them during simulation. These two models are developed using two different software packages – BondSim for development of dynamic model and BondSimVisual for virtual model. They can run on two separate computers connected in local net. Established two-way communication, based on named pipe technology offers exchange of necessary information between the models.
Proposed procedure for dynamic analysis is applied on slider-crank mechanism. It is one of the most omnipresent mechanisms in many engineering applications, for instance internal combustion machine etc. It provides convert of rotary into alternating linear motion. Obtained simulation results confirm that proposed approach can be efficiently used for dynamic analysis of any other multibody systems with closed kinematic structure.
Keywords: Slider-crank mechanism, bond graphs, visualization, VTK

1. INTRODUCTION
With methods of modelling and simulation it has opened new trend of analysis of very complex dynamic systems. Analysis of the system behaviour, optimization of system parameters, optimal product design can be obtained without expensive experiments. On the other hand, experiments in some systems are impossible or would be dangerous, and as such inapplicable. The rapid growth of computer power and improving of the graphics performances open possibility to use visualization of systems in analysis of system behaviour. Development of tools for design of virtual models became very popular and the subject of many studies. Visualization and object oriented approach in system dynamic analysis are announced as future trends in the computer industry in [4], in which the core characteristics of object-oriented toolkit for 3D graphics and visualization are presented.
With help of visualization, the modelling and simulation of engineering problems are considerably facilitated. Visualization of multibody systems enables detection of possible singularities, collisions between components and finally, offers better understanding system function in whole. These are the reasons why development of virtual models and their virtual environment are became standard tool in off-line programming on industrial robots. Visualization is also included in popular software for dynamic analysis such as Modelica [7], MATLAB/Simulink [8], 20-SIM [8], and the others.
We propose development of two models of planar multibody system with closed kinematic structure – dynamical and visual, using two software packages. Dynamic model is developed by bond graphs in

graphical environment of object oriented software BondSim [5]. BondSimVisual is used to design virtual model. During simulation these two models, which can run on different computers connected in local network, exchange the information.

2. DYNAMIC MODEL OF SLIDER-CRANK MECHANISM

The basic idea of the paper is explained on example of a slider-crank mechanism. It is one of the most popular mechanisms to convert the rotary to the liner alternating motion; it was found in the drawing of Leonardo Da Vinci. As shown in Fig.1a, it consists of three parts: the crank shaft, the connection rod and slider. One end of the slider crank is connected to the ground and other to the connection rod by a revolute joint. The other end of the connection rod is connected to the slider by a revolute joint. Finally, slider is connected to the ground by a prismatic joint forming thus the closed kinematic structure with one degree of freedom.

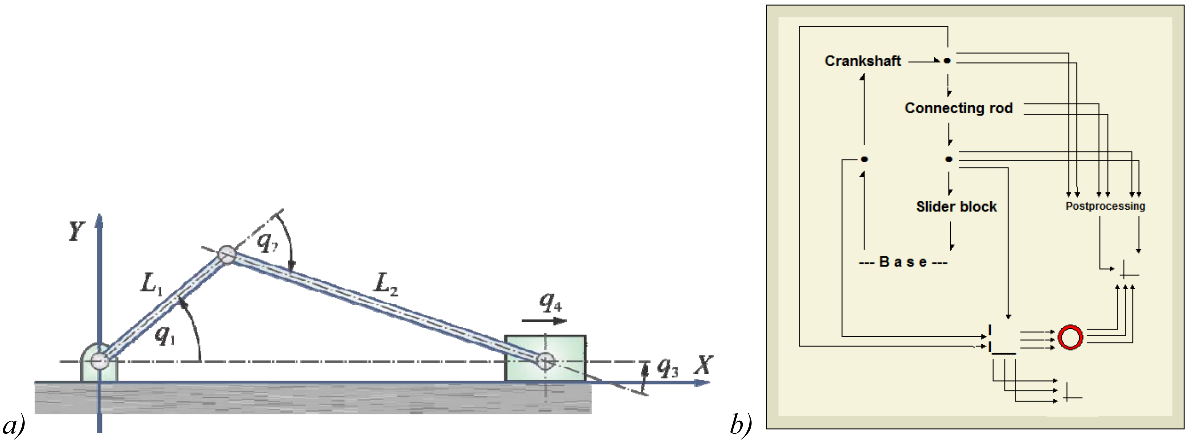


Figure 1. Slider-crank mechanism: a) Scheme; b) Bond graph model – system level.

Dynamic model is realized using bond graphs by BondSim. It is taken from [3] and modified just a little to provide communication with virtual model. On lower right corner there is added a IPC pipe component (denoted by red circle). It establishes communication between dynamic and virtual model and provides exchange information. Dynamic model sends information about joint rotations q_1, q_2 and q_3. It also receives information about slider position from virtual model. Coordinates of slider are fed to display component (in order to compare them with ones obtained on the dynamic side). On dynamic side we can calculate and present on display component any other information that is of interest for analysis of mechanism behaviour.

The crank shaft and connecting rod are considered flexible and realized by three and eight bond graph models of beam finite element, respectively. In this paper, we proposed that crank shaft and connecting rod are made of aluminium with density ρ=2770 kg/m^3, Young's modulus E=7e10 N/m^2 and rectangle cross section 9x10 mm. The length of crank shaft is L_1=0.152 m and length of connection rod is L_2=0.304 m. (Material of system components in [3] is more flexible then aluminium.). The crank shaft is driven by torque in [Nm]:

$$T = 0.01 \cdot e^{(-t/0.167)} . \qquad \text{... (1)}$$

Taking into account value of Young's modulus we expect that the elastic deformations of crank shaft and connecting rod would be quite small. This offers development of slider-crank mechanism components as rigid bodies.

3. DESIGN OF VIRTUAL MODEL

Virtual model of slider-crank mechanism is developed using software BondSimVisual. It is based on VTK C++ library. One of ways how to create virtual model using BondSimVisual, applied in this paper is shown in Fig. 2. Using 3D CAD software CATIA, we developed 3D CAD models of each component of slider-crank mechanism, Fig. 3a and exported them in stl format. It is necessary to take into account the position and orientation of the coordinate system in which the 3D CAD model was developed. It has to correspond to the absolute coordinate system of BondSimVisual. If this is not the case, some transformations have to be done, as shown in the script file. The script file, given in Table

1, defines the configuration of the whole multibody system, i.e. the orientation and position of the joints and bodies relative to the absolute coordinate frame. Finally, the slider-crank mechanism in BondSimVisual window is given in Fig. 3b. Its initial position is depicted in the figure inserted in BondSimVisual window (the right upper corner).

Simulation time is 1.6 s with time step of 1e-3 s and absolute and relative error tolerances 1e-6. The simulation results are presented in Fig. 4. Deformation of the midpoint of connecting rod is of order 1e-7 m, as shown in Fig. 4a. Really a small value of the connection rod deformation justifies the application of virtual model in which the components are considered as rigid bodies.

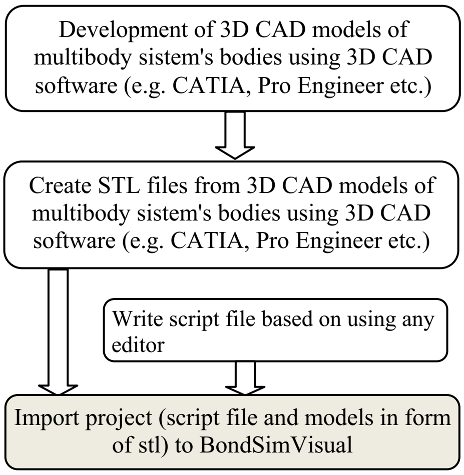


Figure 2. Procedure for development of virtual model.

Table 1. Script file to develop virtual model.

```
!-------- Slider Crank Mechanism -------------------------------------
Robot SCM (euler 0 0 0)
    Joint 1 revolute Z
    Joint 2 ( shift x 152 ) revolute Z
    Joint 3 ( shift x 304 ) revolute Z
;
Part Ground ;
Part Crankshaft ;
Part Connecting_rod ;
Part Slider ;
Set SCM add Ground ( shift x 220 y -15 z -5 ) ;
Render SCM
     color 0.75 0.75 0.75 ;
Set SCM#1 add Crankshaft (shift x 76 z 5) ;
Render SCM#1
     color 0.0 0.6 0.6 ;
Set SCM#2 add Connecting_rod (shift x 152 z 15 euler 180 0 0);
Render SCM#2
     color 0.0 0.2 0.8 ;
Set SCM#3 add Slider (shift euler 0 -90 0 );
Render SCM#3
     color 1.0 0.0 1.0 ;
Probe Point1 SCM#3 refer SCM;
!------------- End -------------------------------------------------
```

Slider-crank mechanism is driven by the torque, given by Eq. 1. It is applied to the crank shaft. The mechanism has just one degree of freedom – the rotation angle q_1. This means that joint rotations q_2 and q_3 and slider translation q_4 are in function of q_1 and they are evaluated during simulation on dynamic side. Dynamic model sends values of joint rotations q_1, q_2 and q_3 to the virtual model. Slider translates as consequence of these joint rotations on the virtual side. To verify the visual model, information of slider position (q_4=X_{svm}) are returned from the virtual to the dynamic side. The signal is compared with signal about slider position evaluated on the dynamic side (q_4=X_{sdm}). These two signals are presented on the same display component, as shown in Fig. 4b. This figure shows that signal with slider position received from the virtual model X_{svm} delays with respect to one obtained from the dynamic model X_{sdm} just for the time needed to send and receive signals.

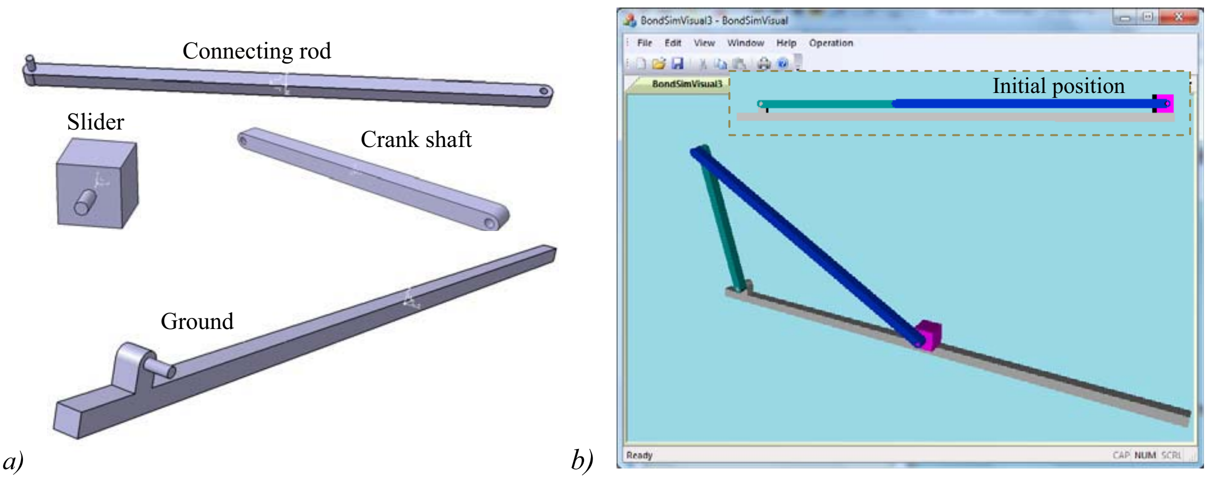
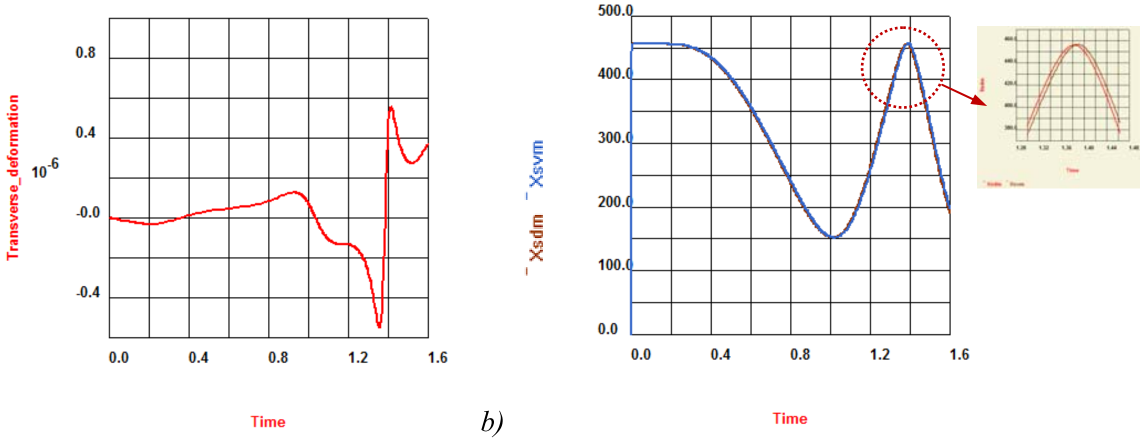


Figure 3. Slider-crank mechanism: a) 3D CAD models of mechanism integrated parts; b) Developed virtual model in BondSimVisual window.



a) *b)*

Figure 4. a) Deformation of connecting rod; b) Slider position obtained on dynamic side (X_{sdm}) and freceived from virtual model (X_{svm})

4. CONCLUSION

In this paper the analysis of behaviour of the planar multibody system based on communication between dynamic and virtual model of the system is presented. The virtual model is created using BondSimVisual. The dynamical model is developed by bond graphs using object oriented software BondSim. During simulation two-way communication is obtained between two models based on named pipe technology, which supports the exchange of information. Two software packages – BondSim and BondSimVisual can run on different computers connected in a local net. The proposed procedure is applied to the slider crank mechanism. Flexibility of its components is neglected because deformation is really small. We plan also to extend our investigation to the multibody systems with flexible links. Also, the approach explained in the paper, can be extended to the analysis of spatial multibody systems with closed kinematic structure.

The presented object-oriented approach for development the dynamic model of system that reuses the components from program library in combination with visualization offers a new power in dynamic analysis of the multibody systems.

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