Advanced Multi-body Modelling in Mechatronics Education

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Abstract. The education of students of Mechatronics study program at Brno University of Technology is highly practically oriented thus the need for clear visual examples is crucial. The paper proposes as an example crankshaft with pistons of general six cylinder combustion engine and different aspects of kinematics and dynamics are explained. The example utilizes modelling of multi-body dynamics with flexible bodies thus advanced techniques of multi-body modelling were used. Clear visual form for education of kinematics and dynamics for students of mechatronics is proposed.

Keywords: Multi-body · Kinematics · Dynamics · Modelling · Flexible bodies · Education

1 Introduction

Physical modelling of an engineering system is indispensable tool for validation of design functionality, optimization of its parameters, verification of control design or other engineering solutions of the system and its components [1, 2]. The importance of advanced modelling is increasing due to high complexity of modern products which are developed faster than ever due to extremely competitive environment on the market. The needs for the sophisticated complex modelling approaches are needed mainly in automotive and aerospace industries which currently take the biggest piece from the engineering market.

The students of Mechatronics study program at Faculty of Mechanical Engineering at Brno University of Technology attend course Kinematics in the second grade and course Dynamics in the third grade of their five year study. Their understanding of the problematics in both of these courses is at the beginning very limited thus the need for practical examples is obvious.

The proposed example demonstrates possibilities of software tools in complex design of a product where different aspects of the future product are explored. The education goal of the example is to present different types of analyses on single example for better understanding of problematics of advanced multi-body modelling and for offering of wider view at kinematics and dynamics of machines.

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The model presents crankshaft with six pistons of general V6 engine. At the first stage, it makes possible to demonstrate kinematic analysis – dependencies between kinematic quantities of particular bodies or visual analysis of the bodies motion.

Analysis of dynamics as the second stage of the proposed example demonstrates dependency between forces acting at the rigid bodies and the motion. The other stage of the example is the investigation of the behavior of the system with flexible bodies and its modal analysis.

The emphasis is also on understanding the suitability of linear time invariant models which can be easily obtained from multibody models and which dramatically decrease computational time for complex systems and present backbone of some of methods for the control design [3] however their usability is often limited.

It is obvious from above that presented example is complex enough to cover different aspects of multi-body modelling and to provide insight to this problematics for students of mechatronics. Let's note that presented example is for educational purposes only.

2 Model

The investigated model (Fig. 1) represents crankshaft with six pistons of general V6 combustion engine [4]. The CAD model which is understood as an input to the presented complex analysis was inspired by open educational materials SolidWorks Tutorial available online.

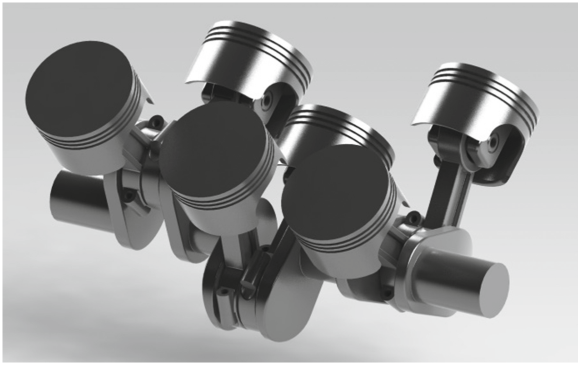

Fig. 1. CAD model of the investigated system – crankshaft with six pistons of a V6 combustion engine

2.1 Kinematics

The elementary goal in the kinematics section is to understand the kinematics scheme in order to represent the movability of the real device correctly and to analyze kinematic dependencies between kinematic quantities of selected bodies.

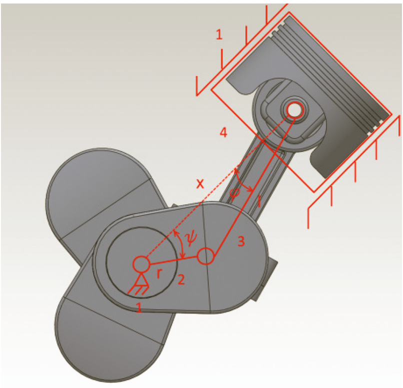

Fig. 2. Kinematics scheme of the single crank-piston mechanism

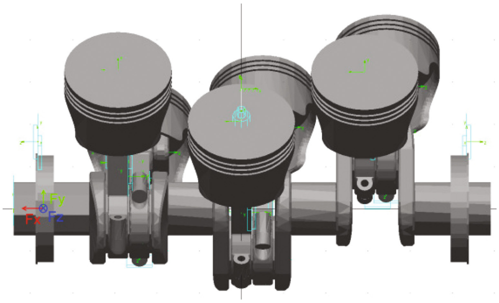

Fig. 3. MBS model prepared for kinematics and dynamics analysis (with coordinate system for measurement of bearing forces – left bearing)

The crank-piston mechanism (Fig. 2) consists of the crankshaft marked by a number 2, rod marked as 3 and the piston marked as 4. The ground body 1 is represented by a motor block. Joints between the bodies 1–2, 2–3, 3–4 are revolute and between 1 and 4 prismatic which results into total one degree of freedom of the crank-piston mechanism. Kinematic quantities of the piston are expressed as a function of angle ψ as follows:

$$x = r\cos\psi + l\cos\varphi, \tag{1}$$

$$r\sin\psi = l\sin\varphi. \tag{2}$$

Equantion (2) is leading to the expression

$$\cos\varphi = \sqrt{1 - \frac{r^2\sin^2\psi}{l^2}}. \tag{3}$$

Substituting (3) to (1) results into the (4) describing a position of the piston

$$x = r\left(\cos\psi + \sqrt{n^2 - \sin^2\psi}\right);\, n = \frac{l}{r}. \tag{4}$$

Velocity and acceleration of the piston is obtained by time derivation of the (4) and (5)

$$\dot{x} = -r\dot{\psi}\left(\sin\psi + \frac{\sin 2\psi}{2\sqrt{n^2 - \sin^2\psi}}\right), \tag{5}$$

$$\ddot{x} = -r\dot{\psi}^2\left(\cos\psi + \frac{n^2\cos 2\psi + \sin^4\psi}{\left(n^2 - \sin^2\psi\right)^{\frac{3}{2}}}\right). \tag{6}$$

The MBS model (Fig. 3) which is at the moment used for kinematics simulation is obtained by the export from the CAD environment. The goal of the example is to demonstrate dependencies between kinematic quantities of the crankshaft and pistons described by Eqs. (4), (5), (6) and to visualize motions of individual bodies. It is also suitable for analysis of relative and absolute motions of the bodies as well as for study of trajectories of selected points.

Figures 4 and 5 present representative example - magnitudes of velocities and accelerations of individual pistons for crankshaft angular velocity 3000 rpm which are approximate operating revolutions of the motor. The various tasks can be studied in very clear and intuitive form.

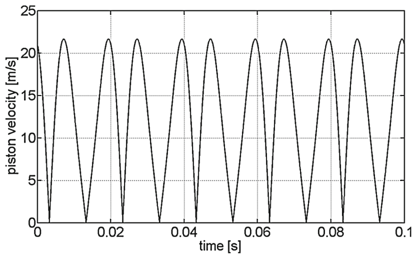

Fig. 4. Magnitude of piston velocity

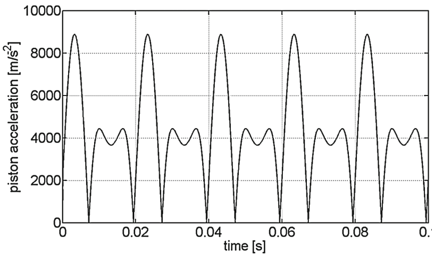

Fig. 5. Magnitude of piston acceleration

2.2 Dynamics

Mass parameters (weight and moments of inertia) of the individual bodies needed for the dynamics analysis are given by the geometry and material defined in the CAD model.

The basic analysis is focused on the investigation of reaction forces in selected joints. Again, some of illustrative examples will be presented.

Figure 6 presents magnitudes of reaction forces measured on prismatic joint between the pistons and the motor block during prescribed constant rotation of the crankshaft 800 rpm, 3000 rpm and 6000 rpm. The model provides also important information about forces acting for example at bearings (revolute joint between the crankshaft and basic body – coordinate system Fig. 3) for different angular velocities of the shaft (Fig. 7). The example clearly presents dependency between loading and kinematic quantities of given bodies (with increasing angular velocity of the crankshaft can be observed increasing forces in the bearing, etc.).

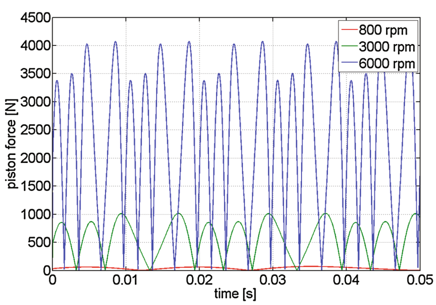

Fig. 6. Piston reaction forces for different angular velocities of the crankshaft

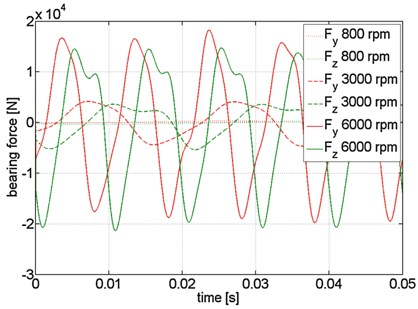

Fig. 7. Radial bearing forces for different angular velocities of the crankshaft

The presented results were obtained from the MBS model with rigid bodies. The model was consequently extended with flexible bodies making possible to perform the modal analysis of the complete mechanism and possibly to investigate whether the eigenfrequencies or their harmonic components interfere with operational range of frequencies of the crankshaft [5].

Again, some of results of modal analysis of free crankshaft as well as of the whole assembly are presented in Figs. 8, 9 and 10.

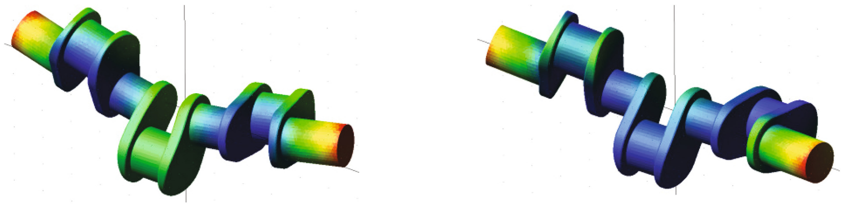

Fig. 8. Modal analysis of free crankshaft - first (left) and second (right) mode (323 Hz; 397 Hz)

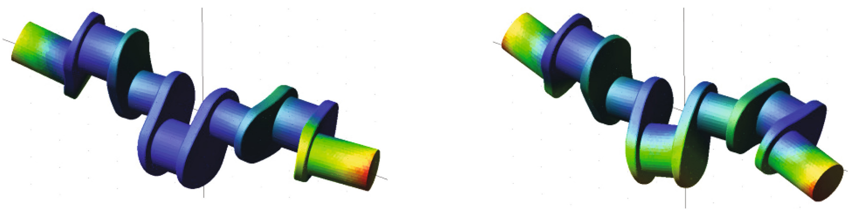

Fig. 9. Modal analysis of free crankshaft - third (left) and fourth (right) mode (742 Hz; 896 Hz)

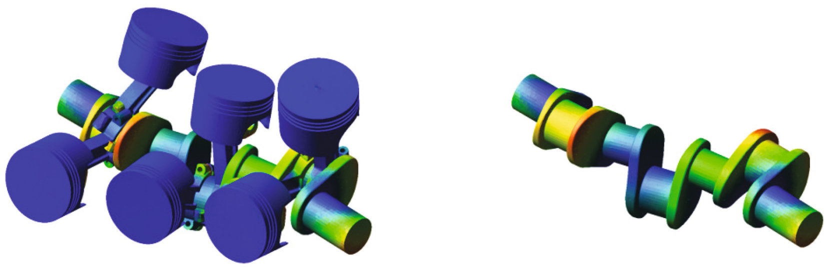

Fig. 10. Example of modal analysis of the complete mechanism - displayed mode at frequency 503 Hz (detail with the crankshaft with pistons invisible - right)

2.3 State-Space Model Based on MBS Model with Flexible Bodies

A linear time invariant state model has due its computational modesty its place in some mechatronic applications. However, some of model information is due to the linearization lost, thus comparison of the linear model behavior with the original MBS model is crucial.

The linear model was in this case based on the MBS model with flexible bodies from previous stage. The input for the linear model is a torque acting around axis of rotation at one of crankshaft ends and outputs are components of the reaction force at the revolute joint between the crankshaft and the ground body (i.e. force in the bearing – coordinate system Fig. 3).

Figure 11 presents comparison of outputs of original MBS model with flexible bodies and the linear model for input constant torque 10 Nm. It can be seen that with increasing time (and angular velocity) model very quickly leaves the area described by the linear model, thus usability of this particular linear model for other applications is poor which can be also important conclusion.

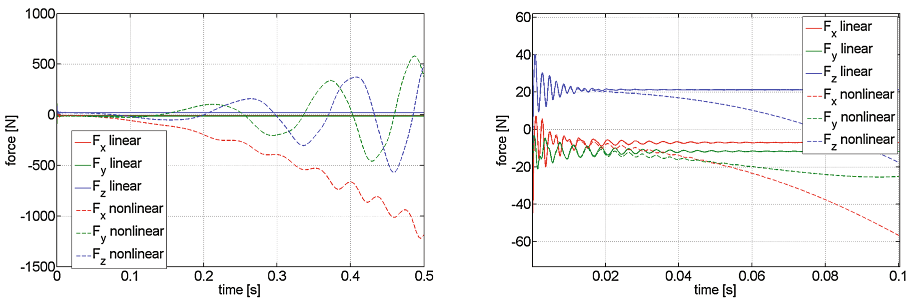

Fig. 11. Components of the reaction force in the revolute joint for the input constant torque 10Nm (detail – right)

3 Conclusions

The paper briefly summarizes possibility of utilization of advanced techniques in multi-body modelling for purposes of education in mechatronics. The presented example provides to students of mechatronics better understanding of the basic problematics of kinematics and dynamics as well as of principles of physical modelling. The example is intended to be practical with clear and illustrative form of visual presentation which is for students attractive.

The model used in the example represents crankshaft with pistons of six cylinder combustion engine and wide range of sub-examples such as kinematics, dynamics of rigid bodies, dynamics of flexible bodies or creating of state-space models can be analyzed. It makes possible to solve various tasks and makes students also familiar with different simulation environments.

Let's note that the example is simplified with strict educational purposes.

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