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AN OBJECT ORIENTED APPROACH TO MODELLING OF FLEXIBLE MULTIBODY SYSTEM: FOCUS ON JOINT CONSTRAINS

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Abstract: *This paper proposes methodology for modelling of the flexible multibody systems that undergo large displacement. Physical modelling of such complex system is obtained using bond graphs. The emphasis of this paper has been placed on modelling of joint constrains. This is done in object-oriented software environment of BondSim®, which enables that an overall complex system be built by combining the components taking from software library.The methods used differs from others is that it is based on velocity formulation and direct integration of the resulting equations. Two numerical simulations are performed and assessed results against the results in the literature.*

Key words: *flexible multibody system, joint constrain*

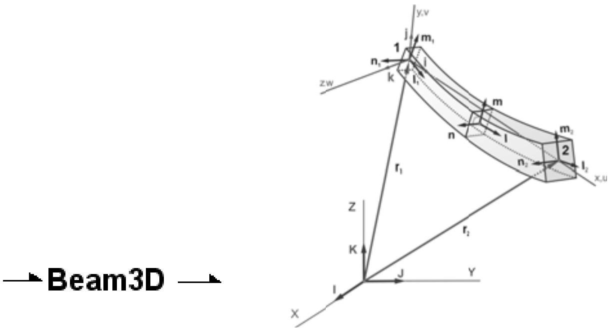
1. INTRODUCTION

Attention of this paper is paid to the object-oriented modelling of the flexible multibody systems with emphasis to modelling of joint constrains. Physical modelling of such complex system is obtained using bond graphs (Karnopp et al. 2000; Damic&Montgomery, 2003). Bond graphs provide modelling of multi-domain systems (electrical, hydraulic, mechanical, etc.) on the same way therefore impose a strong tool in the modelling of mechatronic system. The models of different types of joints, which connect components of the flexible bodies, was developed. This is achieved using object-oriented software environment of BondSim® (Damic &Montgomery, 2003). The methods used differ from others in that it is based on a velocity formulation and direct integration of the resulting equations of the motion. The models are computer generated in form of differential-algebraic equations – DAEs and solved using a backward differential formula BDF. Two numerical simulations dealing with flexible multibody systems are performed in order to verify proposed procedure. The results obtained are in good agreement with the reported in the literature and show how model of complex system can be developed efficiently and with good accuracy.

2. BOND GRAPH MODEL OF FLEXIBLE LINKS

The flexible multibody system can be represented as a collection of elementary components. Flexible components are considered as long slender beams whose models are built as aggregation of bond graph 3D beam finite element (FE) component models (**Beam3D**), Fig.1a. 2D bond graph component has been developed in (Damic,2006; Cohodar et al., 2009.). To develop basic 3D beam component model the co-rotation formulation is applied, (Battini&Pacoste, 2002; Damic&Cohodar,2006). Fig. 1b shows configuration of the basic beam 3D FE. It uses three coordinate frames:

1. Global (inertial) frame, represented by triads (**I**,**J**,**K**),
2. Co-rotation frame (**i**,**j**,**k**) defined on such way that moving of beam finite element with respect to the frame consists only deformation and
3. Section coordinate frame (**l**,**m**,**n**), rigidly attached to the element cross section.



a) b)

Fig. 1. a) Bond graph component of beam element, b) Beam finite element,

Two element nodes of beam finite element are represented by two ports. Flows and efforts ($\mathbf{f}_i^T = \left(\mathbf{v}_i^T \boldsymbol{\omega}_i^T\right)$, $\mathbf{e}_i^T = \left(\mathbf{F}_i^T \mathbf{T}_i^T\right)$ i=1,2) at ports are linear and angular velocities and corresponding forces and moment, respectively, defined in the global frame.

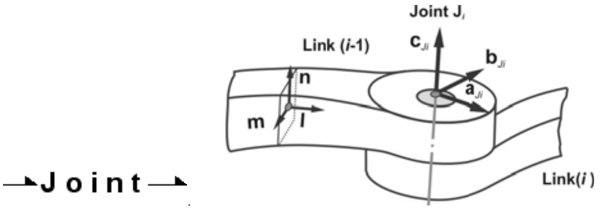
3. BOND GRAPH MODEL OF JOINT CONSTRAINS

The articulation between two consecutive links of robot manipulator can be realized by one of two basic joints: a prismatic or a revolute joint. Other type of joints, for instance cylindrical can be modelled as combination of prismatic and revolute joints. Bond graph model of joint can be represented by component **Joint**, Fig. 2a with two power ports, described by pair vectors – flow and effort. Let joint (i) connect link ($i-1$) to link (i), Fig.2b. The flows at left and right ports are represented by vectors composed of linear and angular velocities of link (i-1) $\left(\mathbf{v}_{i-1}^T\ \boldsymbol{\omega}_{i-1}^T\right)^T$ and link (i) $\left(\mathbf{v}_i^T\ \boldsymbol{\omega}_i^T\right)^T$, respectively (expressed in the global frame). If joint i is revolute the angular velocity of link i with respect to link (i-1) can be expressed in the joint coordinate frame $\left(\mathbf{a}_{J_i}\, \mathbf{b}_{J_i}\, \mathbf{c}_{J_i}\right)$ as:

$$\boldsymbol{\omega}_{i,i-1}^{J_i} = \begin{pmatrix}0 & 0 & \dot{\theta}_i\end{pmatrix}^T, \tag{1}$$

where θ_i is angle of rotation. In the case of the prismatic joint (with joint variable d_i) relative linear velocity is given by:

$$\mathbf{v}_{i,i-1}^{J_i} = \begin{pmatrix}0 & 0 & \dot{d}_i\end{pmatrix}^T. \tag{2}$$



a) b)

Fig. 2. Joint: a) Bond graph model, b) Scheme joint constrain

Development of revolute joint model is based on the assumption that it is rigidly attached to the previously beam element. Thus, joint orientation can be defined through the orientation of the end right cross-section (denote with index 2 in Fig.1a) using rotation matrix $\mathbf{R}_2 = \left[\mathbf{l}_2 \quad \mathbf{m}_2 \quad \mathbf{n}_2\right]$.

The joint orientation with respect to the right end cross-section does not change and can be represented by a constant matrix $\mathbf{R}^2_{J_i} = \left[\mathbf{a}^2_i \quad \mathbf{b}^2_i \quad \mathbf{c}^2_i\right]$. The joint orientation with respect to inertial frame is defined by:

$$\mathbf{R}_{J_i} = \mathbf{R}_2 \mathbf{R}^2_{J_i}. \tag{3}$$

For the revolute joint, relationship between angular velocities at the output and input ports is defined by:

$$\boldsymbol{\omega}_i = \boldsymbol{\omega}_{i-1} + \boldsymbol{\omega}_{i,i-1} = \boldsymbol{\omega}_{i-1} + \dot{\theta}_i \mathbf{R}_2 \mathbf{R}^2_{J_i} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}. \tag{4}$$

For prismatic joint linear velocity at the output port can be expressed as:

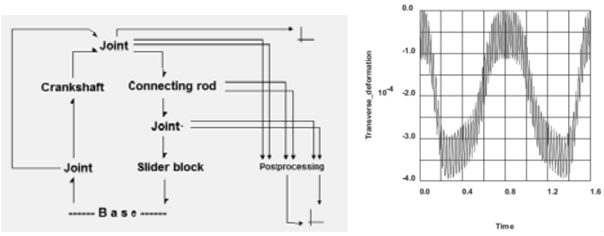
$$\mathbf{v}_i = \mathbf{v}_{i-1} + \boldsymbol{\omega}_{i-1} \times (\mathbf{R}_2 \mathbf{R}^2_{J_i} \begin{bmatrix} 0 \\ 0 \\ d_i \end{bmatrix}) + \mathbf{R}_2 \mathbf{R}^2_{J_i} \begin{bmatrix} 0 \\ 0 \\ \dot{d}_i \end{bmatrix}. \tag{5}$$

4. NUMERICAL EXAMPLES

To demonstrate and verify applicability of proposed models two numerical examples are considered in this paper: slider-crank mechanism, and two-component robot arm. In both simulations the time step is 1e-3 s and error tolerance 1e-6.

4.1 Slider-crank mechanism

To validate the models a flexible slider-crank mechanism is adopted as the first numerical example. Bond graph model of the slider-crank mechanism (Fig.3a) consists of a slider block, crankshaft and connected rod that are connected by the revolute joint. Crankshaft performs only a rotation and is connected to the ground by a revolute joint. Motion of the other side of connected rod is restricted to the horizontal siding plane. The slider block is modelled as a massless particle. The lengths of the crankshaft and connected rod are 0.5 m and 1 m, respectively. The dimensions of cross-section area of both components are the same: H=50 mm and W=5 mm, as well as are the material properties: modulus elasticity is E = 2.1e10 Pa, density ρ = 7.8e3 kg/m^3. The mechanism is initially in the horizontally and straighten position and performs the motion under the influence of its own weight. The mid-point deflection of connection rod is shown in Fig.3b and is in a good agreement with results reported in (Gerstmayr&Schoberl,2006).

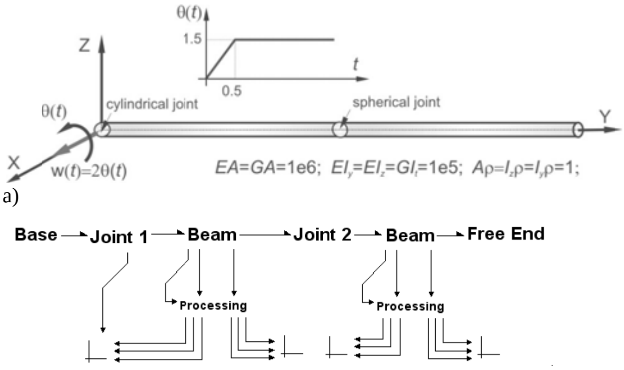


a) b)

Fig. 3. a) Bond graph model, b) Deflection of mid-point of driven rod

4.2 Two-component robot arm

The second numerical example is the two-component robot arm, taken from (Ibrahimbegovic&Mamouri, 2000) and (Kromer et al., 2004). Fig. 4 presents geometry and physical properties of the robot structure. Links are interconnected by a spherical joint. The left side of the first link is connected to the base by a cylindrical joint and subjected to the prescribed displacement and rotation as shown in Fig.4a. Both links are discretized by ten finite elements components.



a)

b)

Fig. 4. A two-component robot arm: a) Scheme, b) Bond graph model

Simulation interval is set to 3 s. Displacement components of free end link are depicted in Fig.5. The results agree well with that obtained in (Ibrahimbegovic&Mamouri, 2000) and (Kromer et al., 2004).

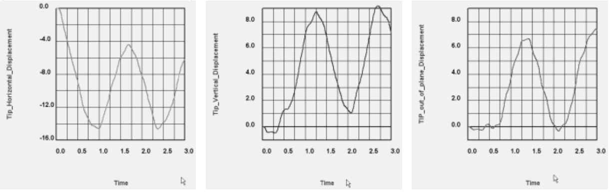


Fig. 5. Tip displacement components

5. CONCLUSION

In this paper, systematic development of the model of a constrained flexible multibody system has been demonstrated where special attention has been focused on modelling of the joint constrains. Due to component model approach each developed component can be put in the library and taken out of it when developing new systems. Several numerical simulations are carried out to test accuracy of developed model and their results are compared with the results of other authors showing good agreements. The proposed method can be successfully applied to modelling and simulation of other mechatronics systems as well.

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