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MODELING AND SIMULATION OF THE SELF - EXCITED STICK-SLIP SYSTEM USING BONDSIM TOOLS

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Abstract. *This papers presents bond graphs modeling and simulation of the second order self-excited system using Bondsim Simulink library. The application of Bondsim elements is based on Fakri transformation of bond graphs into block diagrams. Using an example of a mechanical self-excited stick-slip system, it is shown that the use of Bondsim library will simplify the modeling and simulation.*

Key words: *Stick - slip System, Bond Graph, Matlab/Simulink, Bondsim Library.*

1. INTRODUCTION

Often in engineers practice there is a need for minimization or maximization of the friction force like in rolling or breaking process. The problem control of self-excited systems is very difficult because of friction-induced vibration. Self-excited vibration can be frequently noticed in everyday situations, not only in engineering practice [1-3]. Noise and wear appear to be their undesirable and avoided results.

Modern system requires a very high operating precision as necessary for working. Namely, the proper operation of various types of manipulators in modern automatic control system requires a very high operating precision (as medical manipulators or an assembly of electronic elements). It is very dangerous for human health or life to use self-excited systems. Because, after all inveigling arguments, there is a need to reduce the amplitude of these vibrations. This problem can be solved by additionally influenced external harmonic excitation for the amplitude vibration minimization. In some cases it is impossible to use absorbers. The emerging stick-slip vibration is unavoidable. It is characterized by a

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displacement-time evolution which has clearly defined stick and slip phases in which the two surfaces in contact respectively slip over each other. The motion is governed by a static friction force in the stick phase and a velocity dependent kinetic friction force in the slip phase. The quasi-harmonic friction-induced vibration has a nearly sinusoidal displacement-time evolution and the motion is initiated and maintained in the slip phase.

In that case external harmonic oscillation can help to limit the vibration amplitude. This paper illustrates the results of modeling and simulation of self-excited systems with external harmonic oscillation using bond graph and Bondsim Simulink library.

One of approach for deriving a mathematical model is by using bond graphs [4-6]. The bond graph models can be used as simulation models by analyzing different physical systems (electrical, mechanical, hydraulic systems, etc.), and their combinations (electro-mechanical, mechanical-hydraulic systems, etc.). One of their advantages is that complex systems can be divided into simple elements using the bond graph.

The fundamental advantage of this modeling is that it is based on the central physics concept-energy (the bond graph consists of components which exchange energy or power using connector bonds linking them). The power is a product of two variables, namely, effort *e* and flow *f*. The factors of power effort and flow have different interpretations in different physical domains (mechanical, electrical, hydraulic, thermal, chemical systems).

2. Bond Graph Modeling of Self – excited Systems

Figure 1 presents a mechanical self-excited system that is very frequent in real life. The system is additionally influenced by external harmonic excitation *U(t).* A rigid body weight *m* rests upon the longitudinally undeformable belt. The body is moving at constant velocity $v = \dot{x}$, where *x* is distance from equilibrium point whereby the force in the spring equals zero. The body is joined by a viscous element with damping coefficient D_2. If damper had not existed, the system could not have worked because, without it, the amplitude of vibration would have been greater. Nonlinear friction force F_{nl} depends on: the velocity of relative motion, static friction force and the sign of relative acceleration *w*. The body is on the other side joined by the viscoelastic element described by the Voight model (parallel connection spring rate *k* and resistance damper element with damping coefficient D_1). The external excitation can be expressed by expression:

$$U(t) = U_0 \cos \Omega t = U_0 \cos \frac{2\pi t}{T} \tag{1}$$

where: U_0 - excitation amplitude, Ω - excitation frequency, T – time of oscillation.

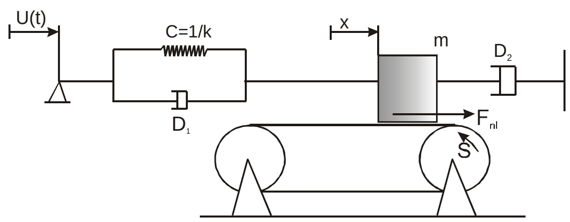

Fig. 1. Principal Scheme of the Second Order Self-excited Mechanical System

In order to understand the creation of bond graphs, it is first necessary to describe a systematic way of writing them. In this mechanical system external oscillation *U(t)* and nonlinear friction force F_{nl} disturb body from its equilibrium state. They represent flow source S_{e1} and S_{e2} in Figure 2. The low of conservation energy is respected because all power from flow source is divided in other four elements of system. They are: flowing accumulator *C* (spring), effort accumulator *I* (mass) and resistors R_4 and R_5 (damper viscous elements with damping coefficients D_1 and D_2). In this case, all the elements have the same velocity and the same flow. There exists a common junction with the identical flow (serial or 1 junction). The flows on the bonds attached to a 1-junction are equal (Equation (2) and the algebraic sum of the efforts is zero (Equation (3):

$$f_1 = f_2 = f_3 = f_4 = f_5 = f_6 = f \tag{2}$$

$$e_1 - e_2 - e_3 - e_4 - e_5 + e_6 = 0 \tag{3}$$

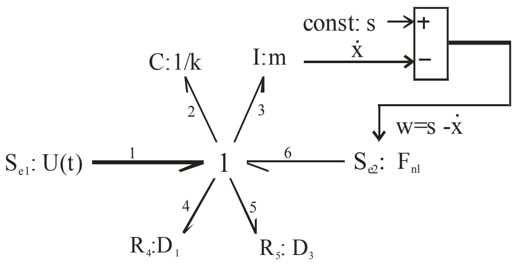

Fig. 2. Bond Graph Model of the Second Order Self-excited Mechanical System

The signs in the algebraic sum and direction of power are determined by the half-arrow direction in a bond graph. Causality is the basis for understanding the system operation and modeling. The relationship between the factors of power is established by causality. The causal stroke indicates the direction in which the effort signal is directed and gives us information about the nature of equations: algebraic, differential or integral. The input and the output are characterized by the causal stroke. Detailed description can be found in [4-7], while it is here described as only applying to self-excited systems (Fig. 3).

In our case the external harmonic excitation and nonlinear friction force get in effort as starting information and determine the causality of effort source. Elements *C* and *I* have integral causality. At a 1-junction only one bond should bring the information about flow. Only one bond should be open-ended and this constitutes the causality of resistive elements R_4 and R_5.

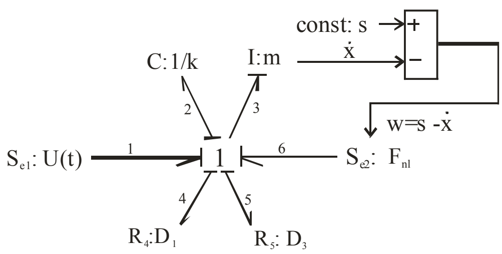

Fig. 3. Causality Bond Graph Model of the Second Order Self-excited Mechanical System

3. MODELING OF SELF – EXCITED SYSTEM USING BONDSIM SIMULINK LIBRARY

The modern, block-oriented program package Matlab/Simulink that does not accept, as input, simulation models in the form of bond graph models, gives the possibility of forming the additional tools in order to enable direct acceptance of the bond graph models. The Bondsim Simulink library for direct acquisition of Simulink simulation models from bond graph models, without using state-space equations, was realized at Faculty of Electronic Engineering in Niš, Yugoslavia. This library contains elements (blocks) which were derived from bond graph elements based on the knowledge of the causality and the appropriate functional relations between inputs and outputs. The elements of this library and their application are described in detail in [8-10], while the method of the direct transformation of causal bond graph models into the block diagrams (Fakri transformation) is described in [7].

In order to facilitate the translation of the bond graphs into block diagrams, the following notions are introduced: owner bonds of junctions, internal and external bonds, owner blocks of junctions (0-junction and 1-junction Bondsim elements) and constitutive blocks (other Bondsim elements). The owner bonds of junction, internal and external bonds are shown in Fig. 4.

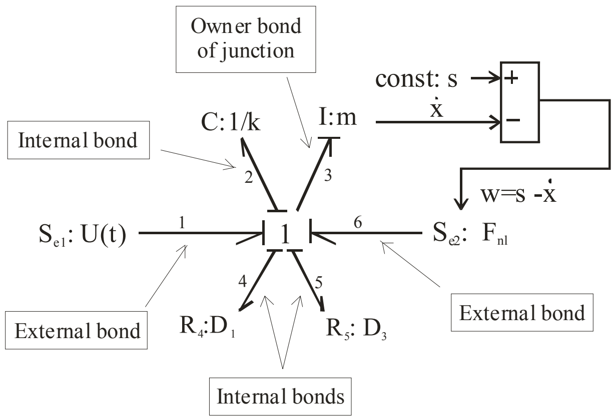

Fig. 4. Some Transfer Elements

The causal bond graph model, shown in Fig. 4, consists of one junction. It is a 1-junction (common flow junction). The owner bond is the number 3 connected with I bond graph element and requires I Bondsim element placed behind 1-junction Bondsim element in block diagram given in Fig. 5. The bonds number 2, 4 and 5 linked to C, R_4 and R_5 bond graph elements are internal bonds and require local feedback loops with C and two R Bondsim elements in the block diagram. The bonds number 1 and 6 (effort sources, SE bond graph elements) are external (no local feedbacks). The owner block of junction 1 is presented in the block diagram by 1-junction Bondsim element which realizes the constitutive relation of this junction ($e_3 = e_1 + e_6 - e_2 - e_4 - e_5$).

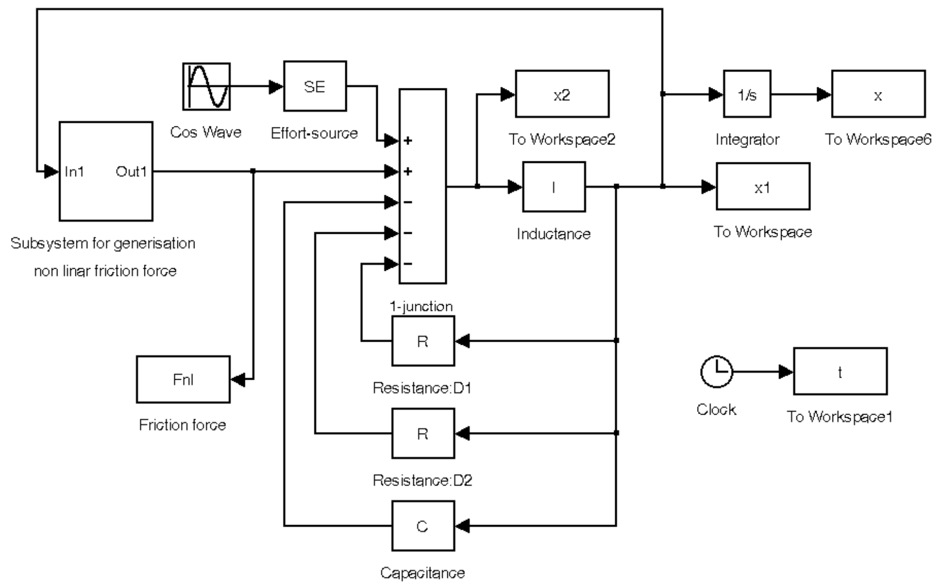

Fig. 5. Bondsim Block Diagram of the Second Order Self-excited System with Subsystem for Generating Nonlinear Friction Force

4. SIMULATION RESULTS

The Simulink Bondsim block diagram, given in Fig. 5, has further parameters: m=4kg and C=0,04mN^{-1}, assuming D_1=D_2=0. Belt velocity has constant value 0.16 m/s. Figure 6 shows a block diagram subsystem for generating nonlinear friction force F_{nl}. The dependence of F_{nl} on relative velocity w and its sign is shown in Figure 7. The dialog box of Simulink Look-Up Table, used for realization of nonlinear friction force F_{nl} , is shown in Figure 8.

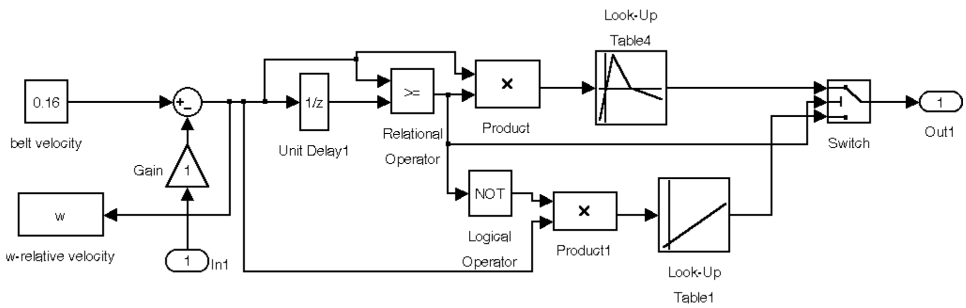

Fig. 6. Subsystem Bloc Diagram for Generating Nonlinear Friction Force

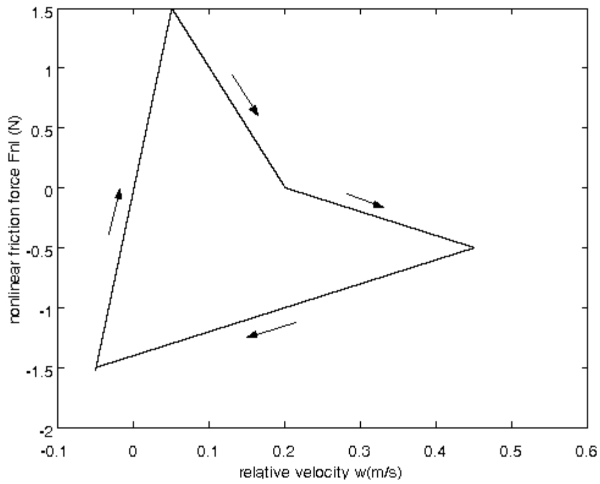

Fig. 7. Graph of Nonlinear Friction Force

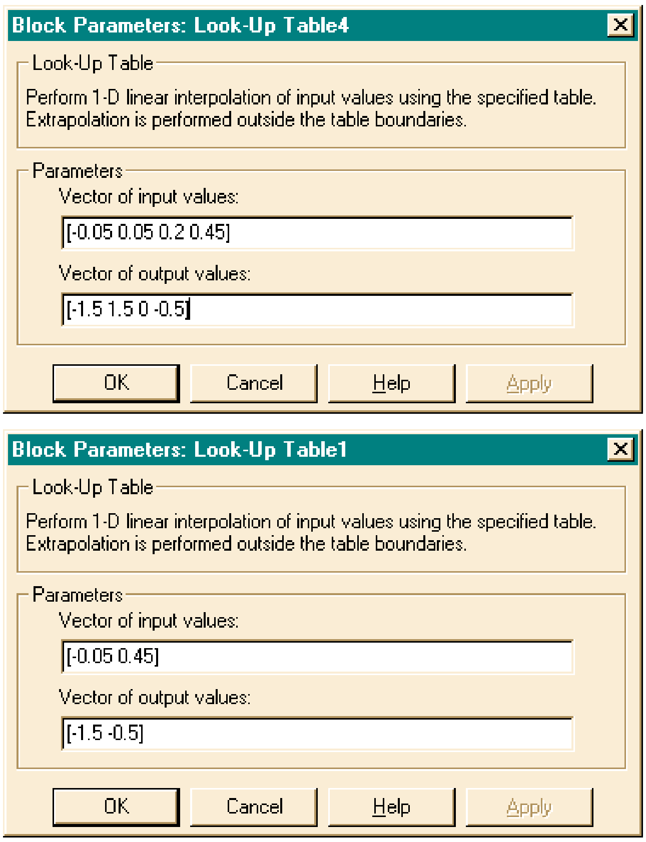

Fig. 8. Dialog Box of Simulink Look-Up Table Block

This investigation tends to find out if it is possible to limit the maximal amplitude with external excitation. When amplitude of excitation frequency equals zero (U_0=0 *N*), the stationary system is out of equilibrium because of friction force action. The stationary system motion takes the form of one-periodic vibration shown in Figure 9a and corresponding phase diagram in Figure 9b. The resulting motion of self-excitation after external harmonic oscillation with amplitude U_0=1.5 *N* with excitation frequency $\Omega=\pi*0.05$ *rad/s* and $\pi*0.08$ *rad/s* and corresponding phase portraits are shown in Figures 10a, 10b, 11a and 11b. The amplitude is more than 50 per cents reduced in comparison with the system without external excitation after choosing corresponding value damper coefficients D_1 and D_2. The smaller value of external frequency increases the period of system oscillation observance.

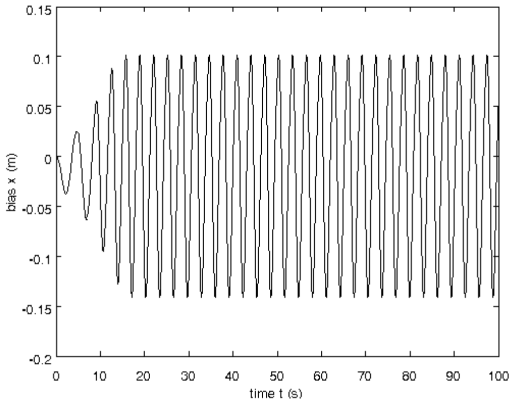

Fig. 9a. The result of Simulation of Self-excited System for Further Parameters: U_0=0 N, D_1=D_2=0 Ns/m, m=4 kg, C=0.04 mN^{-1}

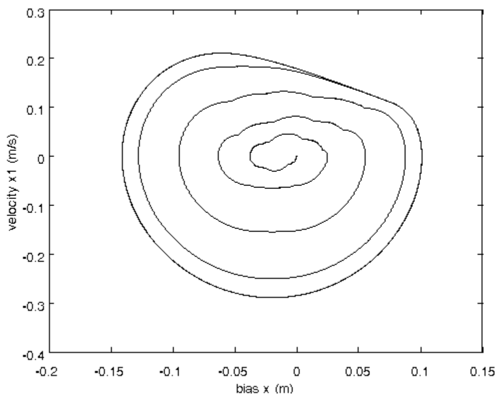

Fig. 9b. Phase Portrait for Further Parameters: U_0=0, D_1=D_2=0 Ns/m, m=4 kg, C=0.04 mN^{-1}

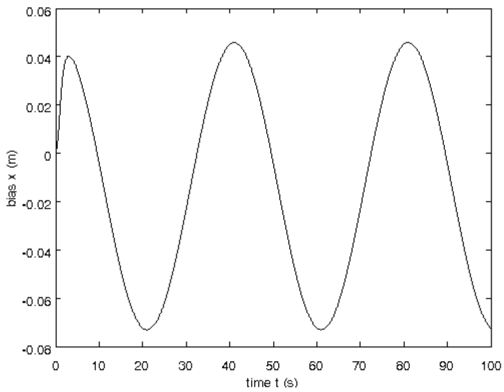

Fig. 10a.Result of Simulation of Self-excited System for Further Parameters: U_0=1.5 N, D_1=10 Ns/m, D_2= 20 Ns/m, m=4 kg, C=0.04 mN^{-1}, $\Omega=\pi*0.05$ rad/s

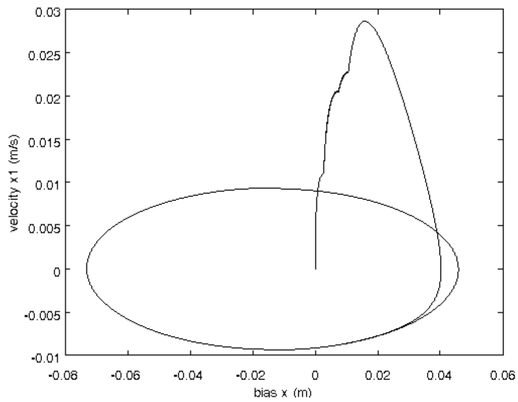

Fig. 10b.Phase Portrait for Further Parameters: U_0=1.5 N, D_1=10 Ns/m, D_2= 20 Ns/m, m=4 kg, C=0.04 mN^{-1}, $\Omega=\pi*0.05$ rad/s

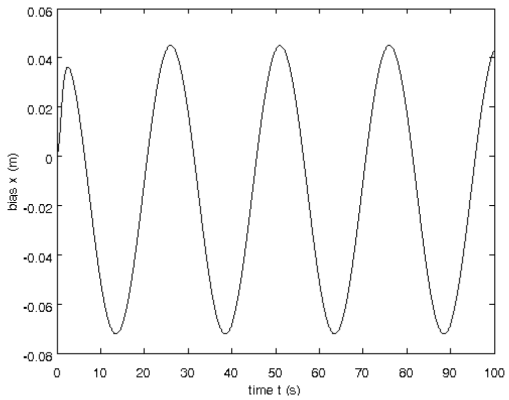

Fig. 11a.Result of Simulation of Self-excited System for Further Parameters: U_0=1.5 N, D_1=10 Ns/m, D_2= 20 Ns/m, m=4 kg, C=0.04 mN^{-1}, $\Omega=\pi*0.08$ rad/s

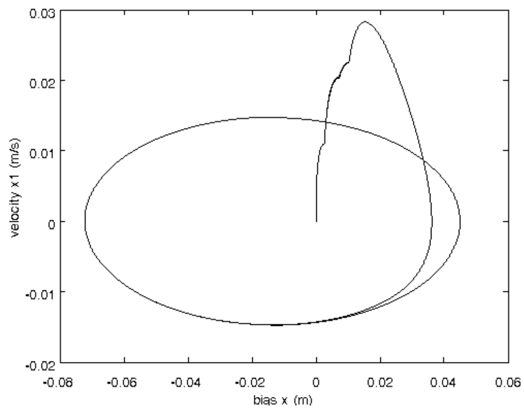

Fig. 11b.Phase Portrait for Further Parameters: U_0=1.5 N, D_1=10 Ns/m, D_2= 20 Ns/m, m=4 kg, C=0.04 mN^{-1}, $\Omega=\pi*0.08$ rad/s

5. CONCLUSION

The modeling and simulation of the second order self-excited system using bond graphs are described in this paper. A method for direct transformation of bond graph models of dynamic systems into the models in the form of block diagrams using Fakri transformation and Bondsim Simulink library is introduced, too. Fakri transformation is a simple, easy and practical method for conversion of bond graph models into their representation by block diagrams and it is a clear and convenient transformation for the application of Bondsim tool. Using the Bondsim library the computational as well as the topological structure of the system is retained. The simple application of proposed method is illustrated using a concrete example of mechanical self-excited stick-slip system.

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MODELIRANJE I SIMULACIJA SAMOPOBUDNOG MEHANIČKOG SISTEMA PRIMENOM BONDSIM ALATA

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U radu se razmatra bond graf modeliranje i simulacija samopobudnog sistema drugog reda primenom Bondsim Simulink biblioteke. Primena Bondsim elemenata je bazirana na Fakrijevoj transformaciji bond grafova u blok dijagrame. Na primeru samopobudnog mehaničkog sistema pokazano je da Bondsim biblioteka značajno pojednostavljuje proces modeliranja i simulacije.

Ključne reči: *Mehanički samopobudni sistem, Bond graf, Matlab/Simulink, Bondsim biblioteka.*