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Simulacija i odstranjivanje stick-slip efekta servosistema sprovodnog aparata hidraulične turbine

Simulation and Removal of Stick-Slip Effect on a Wicket Gate Hydraulic Servomechanism

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Rezime - Trenje je ponovljiv i neželjeni problem koji se javlja kod hidrauličnih sistema i uvek mora da postoji tendencija da se odstrani. U ovom radu je prezentovani frikcioni model servomehanizma preko kog je moguće ostvariti najtačnije rezultate simulacije, kako i način kompenzacije frikcije, preko tehnike koja je prezentovana modelom hidrauličnog cilindra koji se koristi kod sprovodnog aparata hidraulične turbine koji je upravljan servomehanizmom. Prikazan je način modeliranja hidrauličnog cilindra i njegovog servomehanizma, koji su deo mehanizma sprovodnog aparata gde se stik-slip fenomen javlja kod komponenti koji su u kontaktu. Prezentirana teorija i dobijeni rezultati precizno prikazuju okolnosti kada se stik-slip efekt javlja kod hidrauličnih sistema. Simulacija efekta je obavljena korišćenjem softvera Simulink i Hopsan i analiza dobivenih rezultata je prikazana u ovom radu. Odstranjivanje stik-slip efekta je izvedeno pomoću projektovanja kaskadnog upravljanja primenjenog da upravlja ponašanjem sistema i da odstrani pojavu isprekidanog kretanja servomehanizma i hidrauličnog aktuatora.

Ključne reči - kaskadno upravljanje, trenje, hidraulična turbina, stick-slip efekat

Abstract - Friction is a repeatable and undesirable problem in hydraulic systems where always has to be a tendency for its removal. In this paper, the friction model is presented through which the most accurate results are achieved and the way of friction compensation, approached trough technique presented with the mathematical model of a hydraulic cylinder of a hydro turbine wicket gate controlled by a servomechanism. Mathematical modelling of a servo mechanism and hydraulic actuator, and also the simulation of hydraulic cylinder as a part of a hydro turbine wicket gate hydraulic system where the stick-slip phenomenon is present between the system components that are in contact is presented. Applied results in this paper and the theory behind them precisely demonstrate under what circumstances the stick-slip phenomenon appears in such a system. The stick-slip effect is simulated using Simulink and Hopsan software and the analysis of the results are given in this paper. Removal of the stick-slip effect is presented with the design of a cascade control implemented to control the behaviour of the system and remove the appearance of a jerking motion.

Index Terms - Cascade Control, Friction, Hydro Turbine, Stick-Slip phenomenon

I INTRODUCTION

The friction is complex phenomenon which is mainly related to the resistance to relative movement of contacting surfaces. Friction properties have been studied through various models in order to predict and present the frictional behaviour of a hydraulic servomechanism. Stick-slip effect is continuous transition between static and kinetic friction force and vice versa at near zero velocity and lasts until it is removed. During Stick-slip, a system is believed to undergo transitions between a static (solid-like) state and a kinetic (liquid-like) state. [1] Even if the servomechanism is small part of Hydro Power Plant, it is very important part of governing control system. A mathematical model of wicket gate hydraulic servomechanism is presented and also simulated in two modelling and simulation software: MATLAB/Simulink and HOPSAN. Using both of the simulation software is for checking the accuracy of the responses and to compare the obtained results because of no chance to make any experimental activities and measurements in laboratory or directly on wicket gate hydraulic servomechanism. Removing the stick-slip phenomenon of a hydraulic servomechanism is presented trough implementation of Cascade PID controller.

II MATHEMATICAL MODELLING OF HYDRAULIC SERVOMECHANISM

Hydraulic servo system consisted of servo valve which controls hydraulic cylinder is highly non-linear. The primary force causing is the pressure difference across the piston of a servo valve which controls the hydraulic cylinder. Second Newton Law which is applicable in wicked gate hydraulic servomechanism is presented mathematically by the following equations:

$$m \cdot a = \sum F \tag{1}$$

$$\sum F = P_1 A_1 - P_2 A_2 - F_{friction} - F_{load} \tag{2}$$

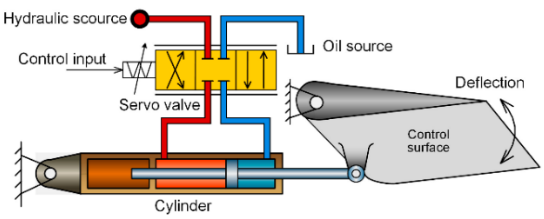

Figure 1. Hydraulic servomechanism

Friction is usually modelled as a discontinuous static mapping between the velocity and the friction force that depends on the velocity's sign and is directly related to the velocity. Due to the fact that the friction does not have an instantaneous response to a change in velocity, i.e. it possesses internal dynamics [3]. The total friction can be divided into different types of friction, which are characterized by the velocity state at which they act and their dependence of that state. Friction is mainly divided on static, kinetic and viscous friction according to Figure 2.

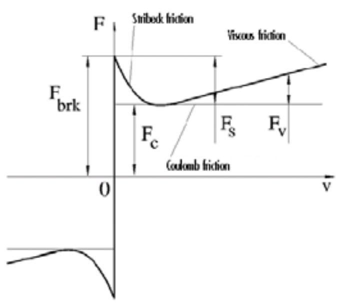

Figure 2. LuGre friction curve

There are several models existing that describe the friction [2], but LuGre model is an extension of Dahal model that captures the Stribeck effect and thus can describe the stick-slip motion. The LuGre model contains only a few parameters, and thus can easily be matched to experimental data. Because of this, obtained results in this paper are presented trough LuGre friction model which is presented with the following mathematic model:

$$\frac{d_z}{d_t} = \dot{x} - \sigma_o \frac{|\dot{x}|}{g(\dot{x})} \tag{3}$$

$$g(\dot{x}) = F_c + (F_s - F_c)^{e^{(-v_2/v_2^2)^2}} \tag{4}$$

$$F = \sigma_0 z + \sigma_1 \frac{d_z}{d_t} + \sigma_2 \dot{x} \tag{5}$$

where F_c, F_s, v_s, σ_2 are representing the static friction, while σ_0 and σ_1 are representing the kinetic friction [4] [5] [6].

Despite the models of LuGre friction, important place in this paper takes the equation that describes the amount of fluid that is flowing through the servomechanism:

$$q_{L1} = C_q w x_d \sqrt{\frac{2}{\rho}(P_s - P_1)};\ q_{L2} = C_q w x_d \sqrt{\frac{2}{\rho}(P_2)} \tag{6}$$

This research is done when the position of the servo mechanism piston is in ideal, central position and if there is no leakage trough the orifices of the mechanism. Mathematical description for this is as following:

$$c_v^{(1)} = \frac{Q_n}{\sqrt{\Delta P_N}} \cdot \frac{1}{x_{v,max}} \tag{7}$$

The relationship between the flow and pressure is described with the following equations [4] [5]:

$$K_{q1} = C_q w \sqrt{\frac{2}{\rho}(P_s - P_1)}\,; K_{q2} = C_q w \sqrt{\frac{2}{\rho}(P_2)} \tag{8}$$

$$K_{c1} = \frac{C_q w x_{vo}}{\sqrt{2 \cdot \rho (P_s - P_1)}}\,; K_{c2} = \frac{C_q w x_{vo}}{\sqrt{2 \cdot \rho \cdot P_2}} \tag{9}$$

Density of hydraulic oil described trough Bulk modulus equation is as important as the other parameters and coefficient that affect the hydraulic servomechanism.

$$Q_i - Q_0 = \frac{dV}{dt} + \frac{V}{\beta_e}\frac{d\rho}{d_t} \tag{10}$$

Because of the controlling function, servo valve is important component in wicked gate servomechanism system. Its transfer function where delay is not considering when moving the spool is described as following:

$$G_{valve}(S) = \frac{1}{\tau \cdot s + 1} \tag{11}$$

Transfer function of the wicked gate hydraulic servomechanism is presented trough the following equation:

$$\frac{Y(s)}{X(s)} = \frac{K_q(A_1 - A_2)}{\left\{M \cdot s^2 \cdot \frac{v_0}{\beta} \cdot s + K_c\right\} + (A_1^2 - A_2^2)^2} \tag{12}$$

Besides the mathematical modelling of the wicked gate servomechanism, the simulation in Simulink and Hopsan and responses from both software are presented in the paper.

Wicked gate hydraulic servomechanism system has a six-state variable non-linear mathematical model described with appropriate differential equations.

III Simulation of Hydraulic Servomechanism When Stick-Slip Effect Occurs

Two software are used to simulate the stick-slip phenomenon in the hydraulic servomechanism in order to obtain appropriate responses and to check their accuracy.

When modelling and simulating stick-slip effect, the most important part is to use the right model to describe the friction force where all of the parameters that are affecting the system are taken into consideration. This could only be achieved with implementing LuGre friction model into the observed hydraulic servomechanism system. LuGre model simulated in Simulink are presented on Figure 3 below.

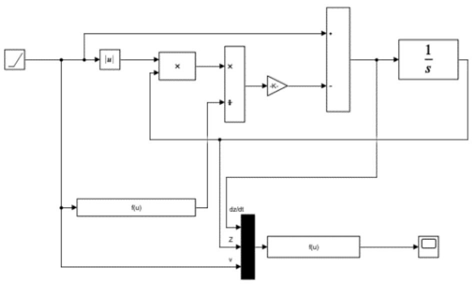

Figure 3. LuGre friction model modelled in Simulink

Given response friction force - time is shown on Figure 4.

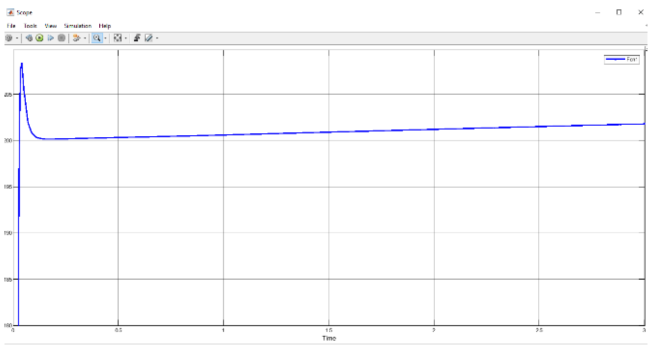

Figure 4. Friction force – time response of LuGre friction model

According to Figure 2, on which is shown response of LuGre friction model where a few representations of friction models are packaged into one model. Same response is shown on Figure 4, where it is clearly demonstrated that LuGre friction model is combination of Stribeck, Viscous friction and Coulomb friction force.

Stick-slip phenomenon is recognizable after a continuous transition between the states of stick into slip and vice versa without occurrence of gradual disappearance of the states of transition between sticking and slipping. Stick-slip phenomenon is present in the system until it is completely removed from the system.

Hydraulic servomechanism system is modelled and simulated in Matlab/Simulink and it is shown on Figure 5.

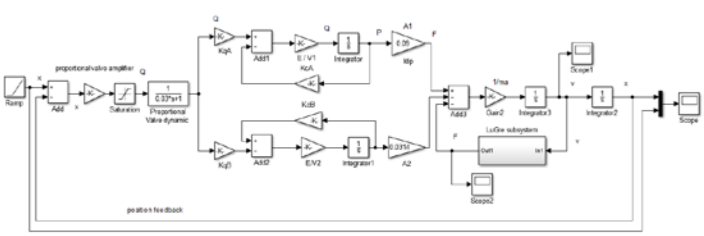

Figure 5. Simulink model of Hydraulic servomechanism system with LuGre friction model subsystem

Hydraulic servomechanism system shown on Figure 5 is combination of the following elements that are affecting the system where the stick slip effect is present: transfer function of servo valve, flow gain trough the servo valve, flow-pressure coefficient, volume of hydraulic cylinder in both chambers, modulus of elasticity etc.

Through the response of the system, it could be concluded that the stick-slip effect is present in the simulated model if transition between sticking and slipping phase is continuous.

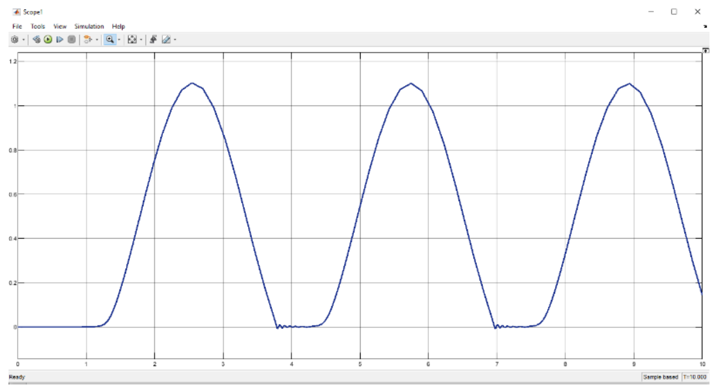

Figure 6. Velocity – time response in a wicked gate hydraulic servomechanism

According to the theory behind the stick-slip phenomenon and the simulated model, response of the hydraulic servomechanism system is represented on Figure 6 and is clearly shown that the continuous transition between sticking and slipping stage without any change in gradual disappearance of the states of transition between both stages is continuous. Velocity – time response is shown because it is very specific and characterizes the appearance of stick-slip effect because the transition between static and kinetic friction force is happening at near zero velocity as it is shown in details on Figure 7, photo of the stage where kinetic friction force exceeds the static friction force.

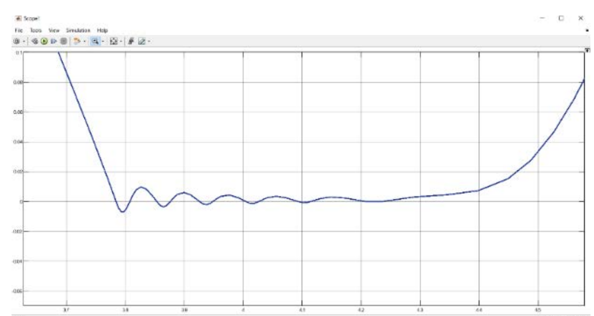

Figure 7. Detail view of the transition between the kinetic and static friction force

Second software, Hopsan which is specialized for modelling of hydraulic and mechatronics systems is used just for comparing the obtained results. Modelling in Hopsan is done with component connecting one to another without defining differential equations for each component or transfer function of the system, but only defining the right values of some default given parameters, depending on the type of the components. Beside the manner of modelling is completely different between both software Hopsan and Matlab/Simulink, and through the given responses could be noted that they should be similar enough one to another and to make a conclusion that stick-slip effect is present in the system modelled in both software independently. Because this paper is about representing the simulation and removal of stick-slip effect of a wicked gate hydraulic servomechanism, it seems like the mass shown on Figure 8 could lead to confusion with explanation that it is an excess element that should not be present in this model. But, because of the principle of working and the algorithm of the Hopsan software, mass is only an element with 0 value that connects the hydraulic part and the force applied on the hydraulic parts.

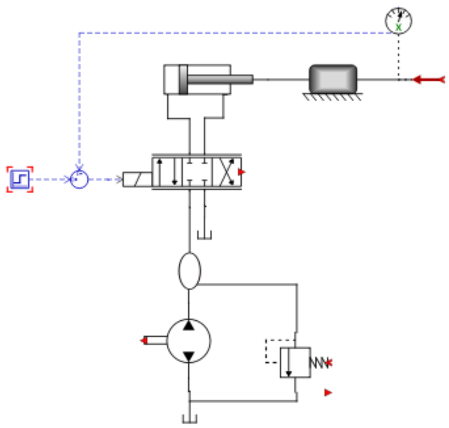

Figure 8. Model of a hydraulic servomechanism in Hopsan

According to the Figure 8, model of a hydraulic servomechanism is done in Hopsan software [6] and the response velocity-time is shown on Figure 9.

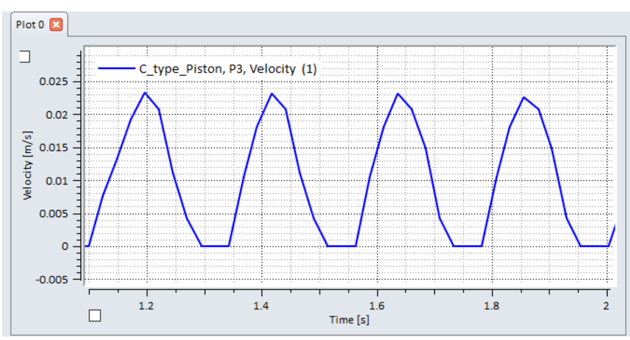

Figure 9. Velocity-time response of a hydraulic servomechanism system done in Hopsan

According to Figure 9, the continuous transition between the static and kinetic friction force i.e. continuous transition between sticking and slipping state and vice versa is noticeable. Comparing Figure 6 and Figure 9, difference in both curves could be noticed, but that is because of the different background configuration of both software and completely different principle of working and calculating the models. But the given curves are slightly different one to another i.e. no significant difference in responses of both software. Conclusion could be made and could be established that stick-slip effect is possible to be simulated with both software, Hopsan and Matlab/Simulink with slight difference in the responses.

IV Removal of Stick-Slip Phenomenon of a Hydraulic Servomechanism System

In this paper, a possible way of removing the stick-slip effect from a hydraulic servomechanism system has been presented.

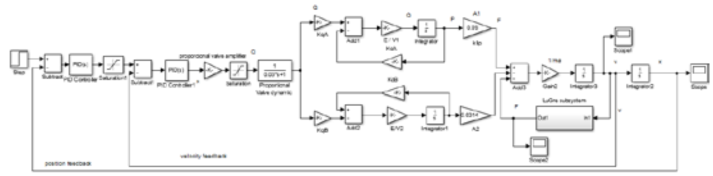

Figure 10. Cascade control of a hydraulic servomechanism with LuGre subsystem

On Figure 10 is shown Simulink model of Cascade PID control of a hydraulic servomechanism model including two PID controllers and are present two feedbacks, velocity and position feedback [7]. Implementing Cascade PID control in a system where stick-slip effect occurs is a successful story because trough the velocity control, the sudden jump of velocity magnitude at near zero velocity is eliminated. If the moment of a sharp increase/decrease at near zero velocity is eliminated when the transition of a state of sticking to slipping and vice versa is overcome, then could be noted that the stick-slip effect of a system is eliminated. On Figure 11 is presented position-time response of a system only with one PID controller with position feedback. According to the given response can be stated that only with position control, the stick-slip effect is still present in the system i.e. the transition between the sticking and slipping effect and vice versa is continuous over time without tendency to be declined which indicates that position feedback control is not a successful method for stick-slip effect removing.

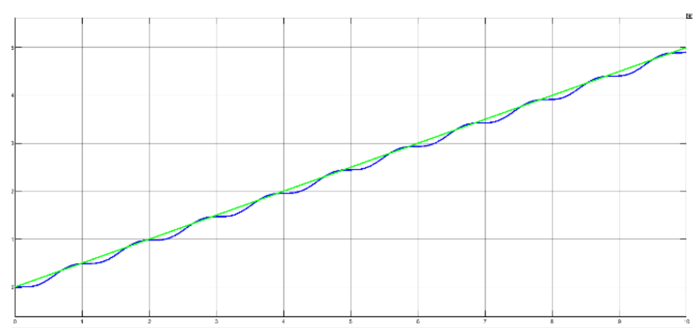

Figure 11. Position – time response of a system with a position feedback

Figure 12 represents the velocity-time and position-time response of a Cascade PID control system where velocity feedback is present in the system. According the responses, is concluded that implementing second PID controller i.e. velocity feedback control, stick-slip effect is completely removed from the system and over time when it becomes stable, remains stable.

Because in this paper two software - Matlab/Simulink and Hopsan are presented, Cascade PID control model is done also in Hopsan in order to compare the obtained results in Simulink.

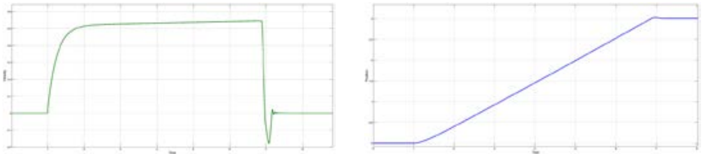

Figure 12. a) Velocity – time response of a system with Cascade PID control – no stick-slip presence; b) Position – time response of a system with Cascade PID control – no stick-slip presence

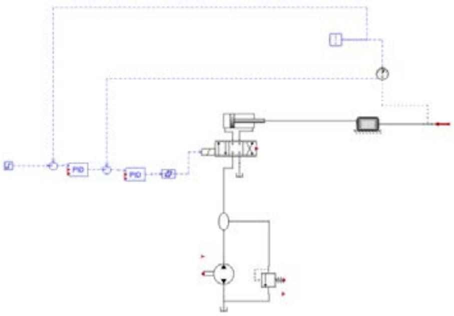

Figure 13. Hopsan model of a hydraulic servomechanism

The model is similar with the one with Cascade control done in Simulink. Both feedback, velocity and position are present in the system which indicates that the responses given in Hopsan can be compared with the one given by Simulink.

Hopsan model of a hydraulic servomechanism is shown on Figure 13.

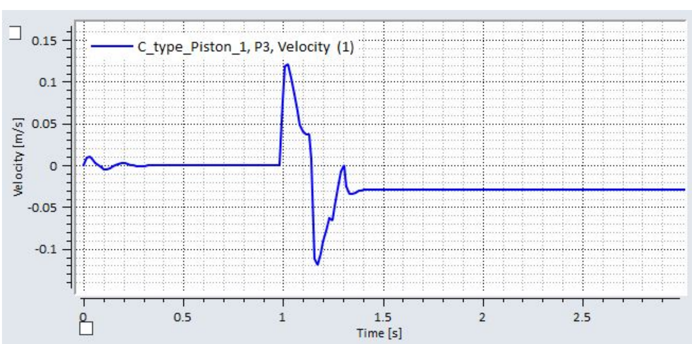

Figure 14. Velocity-time response of a hydraulic servomechanism model in Hopsan

According to the Figure 14 velocity-time response given in Hopsan, can be noticed that Cascade PID control is successful configuration when stick-slip effect is removed from a system while modelling in Hopsan and that the responses are more or less similar in both software which means that Hopsan is software that can be used for modelling hydraulic system and the given responses can be taken as relevant ones.

V CONCLUSION

Mathematical model of a hydraulic servomechanism system, including the transfer function of the components that it contains have been presented. Modelling is performed using Matlab/Simulink and Hopsan software. In addition, simulation is performed in both programs which primary aim is to compare the given responses, as well the accuracy of it. The presence of the stick-slip effect is confirmed by both programs, which led to very similar results. Removing the occurrence of the stick-slip effect is also presented through the simulation made in Simulink and Hopsan by using Cascade PID control i.e. by implementing velocity feedback control in the system because the impact of the stick-slip effect in the system can be removed and that can be done by adding velocity feedback control but not with position feedback control.

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