Optimal Nonlinear Control in MWD assisted Directional Drilling Process

Amir Rouzgard and Kourosh Heidari Shirazi

Abstract—**In the present work an algorithm is proposed for automatic guidance of bit in directional drilling process. In the manual mode control of bit's movement some problems arise due to operational and human inaccuracies which make the actual path differ from the desired one. In this article an automatic control system based on the bang-bang control strategy equipped with MWD (Measuring While Drilling) has been designed to lead the bit to the target. The bang-bang control strategy is one of the optimal nonlinear control methods. According to the kinematic constraints and system's input variables of the present problem this control strategy is suitable and simple to implement. In the first step the kinematic model of the drillstring movement has been derived. In the second step using Matlab-Simulink software, the system's kinematic equations besides some effects such as mechanical behavior of the well, dead zone between the formation and the bit, changing the geological formation during the drilling, time delay in sending and receiving mechanical and electrical signals, and environmental noises have been taken into account and are modeled. Directional drilling has been simulated with empirical parameter values of the well formation in Nargesi field. To study the control system abilities and limitations, results were obtained and studied. It is shown that the control system can generate an appropriate path when the result is compared with an actual drilling data. In the final part the concluding remarks are presented.**

Index Terms— **MWD, bang-bang control, directional drilling, drillstring well interaction.**

I. INTRODUCTION

Navigating the bit and tracking a desired path are the two reasons which led to the invention of MWD system [1]. In directional drilling technology, control of bit movement along the correct path is very important. MWD systems can survey bit movement and have several abilities in leading bit movement along the correct path with the intervention of a human operator. A group of experts (MWD and Directional Drilling, DD. Group) compared data location from MWD output with drilling plan and tried to decrease the differences in bit movement [2]. A human MWD system follows the diagram [3].

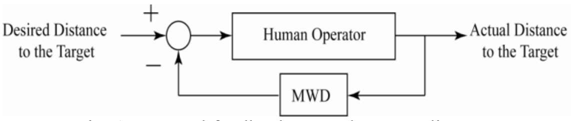

Fig. 1. Manual feedback control system diagram

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II. NOMENCLATURE

ε wave movement domain
ε_t tangential strain
δ_s coefficient of stone
ρ_s density of the drill string
σ_t tangential stress (MPa)
ϑ_s poisson's ratio of the drill string
ω_n natural frequency of the ground
c_L phase velocity of wave movement
c_s sound velocity of mud
E_g modulus of elasticity of the ground
E_s modulus of elasticity of the drill string
f_i the angle between drilling direction and X
L_x length of the drill string in each time
Q properties coefficient of stone
S_0 the angle between KOP and Target
x_1 first phase of wave movement

III. MODELLING

A. Control System for Bit Movement

In the proposed control system for automatic leading the drillstring is depicted in Fig.2. As it is shown the measuring signals form MWD system are conducted by the mud to the processing unit. In this unit the position and orientation of the bit is synthesized. According to the synthesized information the bang-bang type controller sends controlling command to the actuators to exert a $\pm 180°$ rotation to the drillstring for correcting the path.

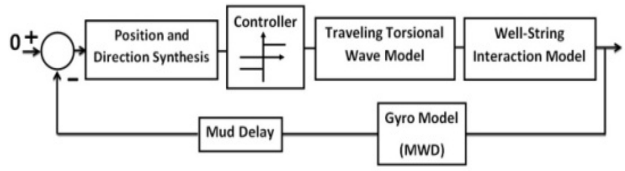


Fig. 2. Feedback control system diagram

B. Position and direction synthesis

Among the five methods for following bit movement [4] the tangential method is chosen in this research. According to this method the system tries to keep slope of the actual path near to the correct slope. In the tip of the bit, there exists a constant bent that can be used to change the bit direction. Depending on the path designer's decision this bent can be adjusted between 0 – 3 degrees. It is assumed that the bent angle cannot be changed during the drilling. The algorithm can be explained as follows:

A line connects KOP (kick off point) to the target (target line of sight), the slope of this line is denoted by S_o. The angle between drilling direction and X is denoted by f. This line in each time is compared with slope of the bit's path f. When slope of the bit's path is more than S_o, the controller rotates the drill string $180°$. Therefore in the next step the path deviation target line of sight become smaller. The smaller the deviation from line of sight the more accurate path generated. Fig. 3 shows two successive steps of the bit movement. Appendix A shows flowchart of guidance procedure for bit movement.

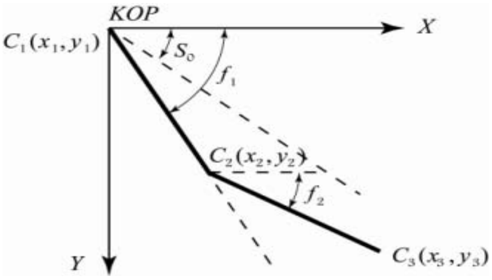


Fig. 3. Two successive steps of bit movement

C. Modeling of Tensional Behavior of the Drill String

To model of torsional compliance of the drillstring a second order linear transfer function is employed [5]. This model contains damping ratio and torsional natural frequency of the string. The natural frequency of drillstring depends on several factors such as: angle of well, mud viscosity and weight on the bit [6] and for our problem is considered to be equal to 6 (rad/sec) [7]. The transfer function is as follows:

$$C_t(s) = \omega_{nt}^2/(S^2 + 2\zeta_t\omega_{nt}S + \omega_{nt}^2)\,. \quad (1)$$

D. Modelling of time delay due to wave propagation

Upon exerting a control command by the actuator on the top of the drillstring a rotational wave moves toward the bottom of the string [8]. Therefore the controlling command reaches to the tip after a delay time *T*. In the Matlab-Simulink this time delay is modeled with time delay block diagram. The following equation describes sinusoidal wave:

$$u_1 = \varepsilon \sin[2\pi(x_1 - C_L t)]\,. \quad (2)$$

where c_L is the longitudinal wave propagation speed and ε is the wave amplitude.

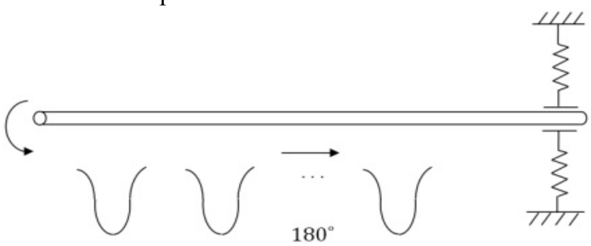


Fig. 4. Longitudinal torsional wave propagation for 180º torsion angle

The time delay for transferring wave from up to down of string can be calculated as follows:

$$T = L_x/C_L\,. \quad (3)$$

E. Modelling of Dead Zone

There always exist a dead zone between the bit and the wall of the well. This has an undesired effect on drilling operation [9]. The dead zone can be modeled in Matlab-Simulink by the nonlinear dead zone block. Fig. 5 shows the dead zone between the two directions of X and Y when on the bit.

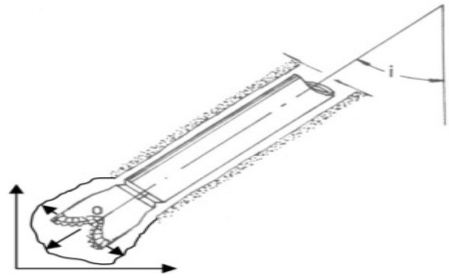


Fig. 5. Dead zone on the bit

F. Interaction between the Bit and the Ground

To show the interaction of the bit and the ground the Spanos and Chevallier [10] modelling method is used. For this purpose damping energy coefficient ζ and Natural Frequency ω_n of each layer are needed.

G. Modelling of Gyro

The dynamic model of the gyros of the MWD system can be estimated by a second order transfer function in S-domain [5],[11]:

$$C_g(s) = \omega_{ng}^2/(S^2 + 2\zeta_g\omega_{ng}S + \omega_{ng}^2)\,. \quad (4)$$

H. Time Delay with Mud Pulse System

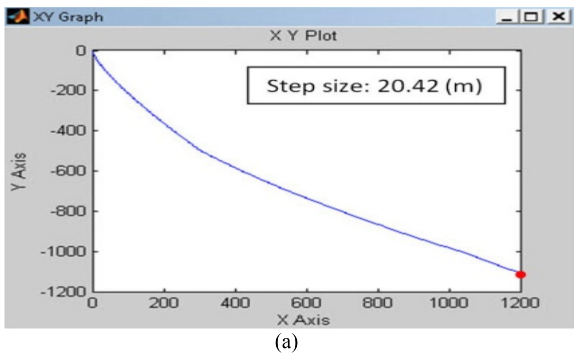
For considering the effect of time delay of mud pulse system in drillstring, first the travelling speed of mud pulse waves should be calculated. The stages of calculating the sound velocity in mud c_s is existed in appendix D. Wave speed in the viscous incompressible fluids is derived from the following equation:

$$t = x/C_s\,. \quad (5)$$

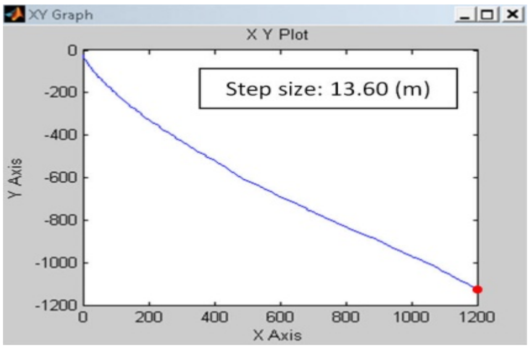
I. Modeling of Disturbances and Noise in MWD System Operation

Undesired effects change the level of energy and shape of signals. Some of these effects are as follows:

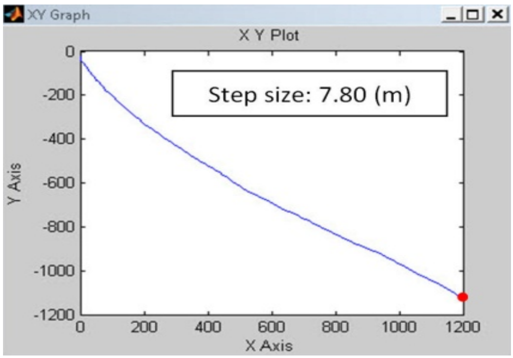
1) Drillstring unpredictable motions
2) Interference of coming waves with the reflected ones
3) Damping of waves in long distances Using the noise block in the Matlab-Simulink, the effects of noises can be added to the systems model.



(a)



(b)



(C)

Fig. 6: Generated path for three different step size (length of drilling collar pipes)

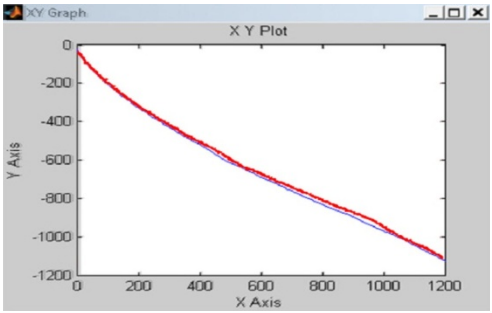


Fig. 7. A comparison between generated path with and without noise effect

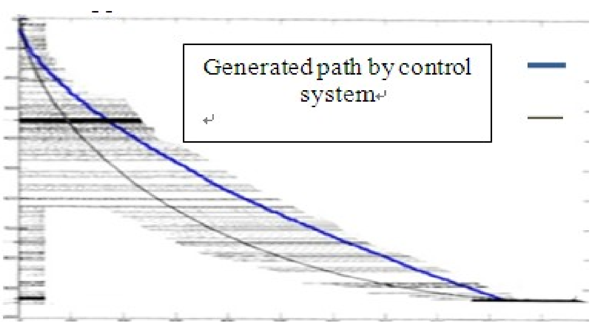


Fig. 8.Well path of No.1 Nargesi field and the simulated path [15]

IV. Simulation

In this section to evaluate the actual response of the control system, actual data of a well from Nargesi field in the south of Iran, has been chosen. The targeting point is located at a depth of 1150(m) and a distance of 1250(m) from the base. The length of drilling collared pipes is considered as step size the drillstring forward progress. The standard length of the drilling pipes are 7.8(m), 13.2(m) and 20.42(m). Also references [12]-[14] are used for extracting some information about layers of the ground. The values of parameters are listed in appendix B.

In all graphs the displacement in the horizontal direction is denoted by X and in the vertical direction by Y. Fig. 6 (a), shows the obtained path using three different step sizes. A comparison between three Fig. 6(a) to (c) reveals that larger the step size, more the curvature of the path and more deviation from target line of sight. Also for three step sizes the bit reaches to the target however the bit doesn't exactly meet the position of the target. Another simulation is performed to show the sensitivity of the generated path in the presence of the noise. The result is depicted in Fig.7. In this figure the generated path in the presence of noise (bold curve) and in the absence of noise (thin curve) are shown and compared. The noise not only makes more fluctuations in the paths, it creates more targeting error. The step size is 20.42(m) for both cases.

V. Conclusions

Fig. 8 compares well No.1 path of Nargesi field [15] which is generated by conventional manual drilling process (thin curve) and the simulated well path using the suggested automatic control (bold curve). It is seen that the simulated well can reach the target. It is concluded that by the presented method and using the geological information of formation not only before practical drilling a digital simulation on drilling process can be performed, a study on best length of drilling collar pipes, bent angle and other parameters of the drilling system can be done.

Appendix A

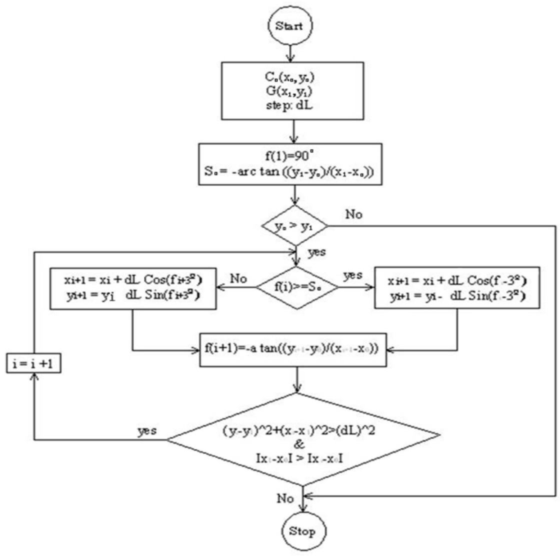


Fig. Appendix A.: Flowchart for position and direction synthesis.

Appendix B

TABLE I: Quantity of Parameters

Parameter	Value	Unit
ξ_g	$1/\sqrt{2}$	---
ξ_t	0.95	---
ω_{n_g}	100	HZ
ω_{n_t}	6	HZ
c_L	6	m/s
c_s	1992.88	m/s

TABLE II(PART 1): QUANTITIES OF PARAMETERS WHICH IS CALCULATED FOR WELL NUMBER ONE IN NARGESSI FIELD

NO.	Ground Layers	Deep (m)	Longitudinal wave time delay (s)	mud pulse time delay (s)	Type of stone	Percentage of constituent	Poisson coefficient	Average of Poisson coefficient	elasticity modulus (MPa)	Average elasticity modulus (MPa)
1	Alluvium	30	0.0049	0.0150	Sandstone	30%	0.24	0.245	11092	10805
					limestone	70%	0.25		10682	
2	Bakhtyari	55	0.0090	0.0270	Sandstone	20%	0.24	0.225	11180	15772
					Marl	80%	0.21		16920	
3	Aghajeri	76	0.0124	0.0381	Sandstone	40%	0.24	0.225	11219	15184
					Marl	60%	0.21		17828	
4	Mishan	111	0.0182	0.0556	limestone	40%	0.25	0.230	11239	14065
					Marl	60%	0.21		15950	
5	Gachsaran	1759	0.2891	0.8826	Sandstone	30%	0.24	0.190	11431	14847
					Shale	20%	0.08		21116	
					limestone	50%	0.25		14390	
6	Asmari	1966	0.3232	0.9865	limestone	Over than 70%	0.25	0.25	14450	14450
7	Jahrom	2173	0.3572	1.0903	limestone	Over than 70%	0.25	0.25	15578	15578
8	Pabdeh	2386	0.3922	1.1972	Marl	Over than 70%	0.21	0.21	18324	18324
9	Goorpi	2408	0.3958	1.2083	Marl	Over than 70%	0.21	0.21	18324	18324
10	Sarvak	2544	0.4182	1.2765	limestone	Over than 70%	0.25	0.25	18890	18890
11	Kajdomi	2899	0.4766	1.4546	Shale	Over than 70%	0.08	0.08	22890	22890
12	Darian	2946	0.4843	1.4782	limestone	Over than 70%	0.25	0.25	20235	20235

TABLE II(PART 2): QUANTITIES OF PARAMETERS WHICH IS CALCULATED FOR WELL NUMBER ONE IN NARGESSI FIELD

NO.	Ground Layers	spring constant (N/m)	Density (kg/m^3)	Average of Density	Mass(Kg)	spring constant (N/m)	ω_n (N/Kg.m)	Q	Average Q	δ	Energy damping coefficient ζ
1	Alluvium	30550	2560	2070	2682.52	30550	3.377	52	94	0.0383	0.0060
			1860					112			
2	Bakhtyari	44592	2770	2602	3371.94	44592	3.639	52	394.4	0.0118	0.0018
			2560					480			
3	Aghajeri	42931	3000	2794	3620.76	42931	3.446	52	308.8	0.0118	0.0018
			2660					480			
4	Mishan	29769	2730	2238	2900.23	29769	3.706	112	332.8	0.0106	0.0016
			1910					480			
5	Gachsaran	41978	3000	2690	3485.98	41978	3.472	52	78	0.0481	0.0076
			2200					32			
			2700					112			
6	Asmari	40856	2700	2700	3498.94	40856	3.420	112	112	0.0280	0.0044
7	Jahrom	44045	2700	2700	3498.94	44045	3.550	112	112	0.0280	0.0044
8	Pabdeh	51809	2680	2680	347303	51809	3.866	480	480	0.0065	0.0010
9	Goorpi	51809	2710	2710	347303	51809	2.8666	480	480	0.0065	0.0010
10	Sarvak	53410	2710	2710	3511.90	53410	3.903	112	112	0.0280	0.0044
11	Kajdomi	64719	2300	2300	2980.58	64719	4.662	32	32	0.0981	0.0156
12	Darian	57214	2740	2740	3550.78	57214	4.018	112	112	0.0280	0.0044

APPENDIX C

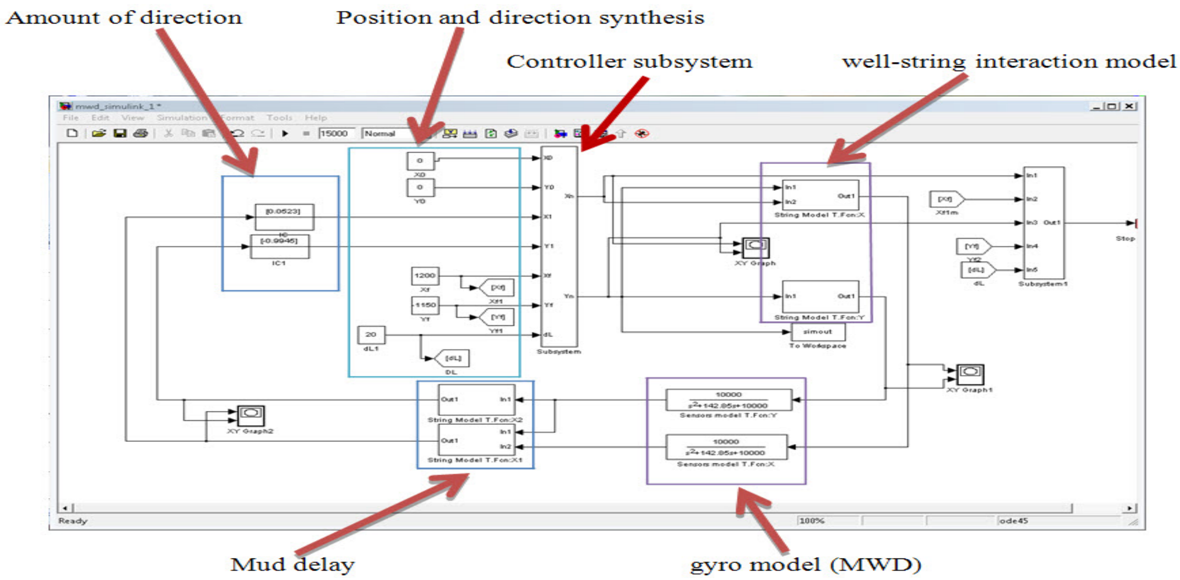


Fig. B.1.: Block diagram of automatic path tracking control in Matlab-Simulink

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