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Experimental Study of Downhole Shock Absorber Based on the Similarity Theory

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Abstract

Based on similarity theory, the similarity criterion of simulation test was derived and the experimental apparatus was established in accordance with the similarity criterion. The similarity criterion deduced by the dimensional theory has a much wider applicability than which deduced by differential physical equations. The experiment device of bottom hole assembly included absorber was designed in proportion of 1 to 10 according to the actual bottom hole assembly. Through the experiment device, the vibration of the drill string with absorber could be obviously observed. Moreover, analysis of the absorber performance experiments under the conditions of different WOB, speed, installation location and elastic stiffness could be carried out.

Key words: Drill string vibration; Similarity criterion; Simulation; Experiment

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INTRODUCTION

In order to solve complex engineering problems, the research method of physical experiments is another basic method in addition to theoretical research, numerical analysis and field observation. Based on the similarity theory, the physical experiments could be designed, and practical engineering problems can be found out and solved by analysis of the experimental data. The universally existing similar phenomena in nature and practical engineering could be effectively explained through the similarity theory[1], which was a bridge between experimental research and engineering application. The similarity theory is mainly composed of three basic principles, and its shaping has experienced three periods: The first stage, French scientist Bertrand first put forward the first similarity theorem based on mechanics equation in 1848, after this theory is proposed, which was widely applied in many fields, and many problems in physical fields such as mechanics, thermodynamics and aerospace dynamics were solved through this theory. The second stage, Russian Фелерман and American E. Buckingham had successively derived the second similarity theorem during 1911 to 1914, which is π theorem. The third stage, the former Soviet Union scholar Kilpi Chief and Kuchmann put forward third similarity theorem in 1930. Thus, the similarity theory has formed a relatively complete theoretical system. In modern science and technology, the similarity theory is mainly used for guidance on the model experiment.

This paper aims to design simulated test equipment in accordance with the similarity theory for studying influencing factors of the Shock absorber performance. Study on drilling string dynamics in vertical wells shows that the presence of violent transverse and longitudinal vibration of drill string and associated wide fluctuation of bit pressure in the process of drilling will not only lead to fatigue failure of drilling string and but also lower the efficiency of rock breaking[2-3]. In order to reduce the vibration of drill string, usually, a vibration absorber for drilling string is included in BHA. Therefore, to provide guidance of design and use of shock absorber, many of scientists and engineers in the field of drilling have done the massive theoretical research work and have established a number of mathematics calculation models. Furthermore, a lot of significant arguments for the engineering practice were proposed, and the main influence factors of shock absorber, such as elastic stiffness, installation location, and drilling parameters were determined[4-6]. However, there are certain differences about the tendency and extent of the influence factors on the performance of the shock absorber. Thus, in order to further study the influence factors of shock absorber performance, experimental research is necessary. In this paper, take the BHA included absorber in drilling as the prototype, the simulated test equipment was designed based on the similarity theory.

1. DEDUCTION OF SIMILARITY CRITERION IN THE SIMULATION EXPERIMENT

There are three main methods to deduce the similarity criterion: law of deduction, equation derivation method and dimensional method. In this paper, the simulation test of similarity criterion is deduced by using dimensional method[6-11]. For convenience, treating the bottom hole assembly as a shaft with uniformly-distributed mass, and discounting for the impact of drill string eccentricity and drilling fluid damping. The parameters and their dimension in this experiment are shown in Table 1.

Table 1
Drill String Dynamics Model Parameter and Dimensions

Physical quantity	Symbol	Dimension
Outer diameter of drill string	D	L
Internal diameter of drill string	d	
Length of drill string	l	
Hole diameter	D_h	
Gyration radius of drill string	r	
Lateral displacement	x, y, z	
Elastic Modulus	E	$ML^{-1}T^{-2}$
Mass of drill string	m	M
Weight on bit (WOB)	w	MLT^{-2}
Friction force on side-wall	f	
Weight of drill string	G	
Density of drill string	ρ	ML^{-3}
Inertia torque of section	I	L^4
Rotation speed	R	T^1
Angle of deviation	α	$L^0M^0T^0$
Elastic rigidity	N	MT^{-2}

To facilitate the dimensional analysis, the parameters in table 1 which have the same dimension were replaced by the same symbol in derivation. For instance, the outer and internal diameter, length, gyration radius of drill string, hole diameter and lateral displacement have the same dimension, so letter 'l' can be used to represent them. Similarly, "F" can be used to represent the WOB, friction force on well wall, and weight of drill string. Angle α is dimensionless, so which can be neglected in derivation. Therefore, there are only eight parameters with different dimension in coefficient matrix, the dimension of the parameters were shown in Table 2.

Table 2
Coefficient Matrix

Basic dimension	l	E	ρ	m	I	F	R	N
M	0	1	1	1	0	1	0	1
L	1	1	-3	0	4	1	0	0
T	0	02	0	0	0	-2	-1	-2

Because of the rank of the coefficient matrix r is 3, the dimensionless deposition of the matrix is 5. And then select l, E, ρ as three separate basic physical quantities, the three basic physical quantities can compose a non-singular matrix, and they can't compose a dimensionless quantity. The dimensionless quantity can be written as:

$$\pi_1=\rho^{k_1}l^{k_2}E^{k_3}m \tag{1}$$

Where π_1 is dimensionless physical quantity, and m is an any physical quantity in coefficient matrix.

Because π_1 is dimensionless, the simultaneous equations can be given by:

$$\left.\begin{aligned} k_1+0+0+1=0 \\ -3k_1+k_2+k_3=0 \\ 0-k_2-2=0 \end{aligned}\right\} \tag{2}$$

k_1, k_2, k_3 can be solved by Equation (2), and the π_1 can be expressed as $\rho^{-1}l^{3}$. Similarly, the other dimensionless physical quantity can be deduced as:

$$\left.\begin{aligned} \pi_1 &= \rho^{-1}l^{-3}m = \frac{m}{\rho l^3} \\ \pi_2 &= l^{-4}I = \frac{I}{l^4} \\ \pi_3 &= l^{-2}E^{-1}F = \frac{F}{l^2E} \\ \pi_4 &= \rho^{\frac{1}{2}}l^1E^{-\frac{1}{2}}R = Rl\sqrt{\frac{\rho}{E}} \\ \pi_5 &= \rho^1l^3l^3N = \frac{F}{lE} \end{aligned}\right\} \tag{3}$$

Set the dimensionless physical quantity of the prototype in Equation (3) equal to the model, the follow equations can be deduced. In the follow equations, the letters with subscript 'm' represents model parameter and the letters with subscript 'p' represents prototype parameter.

$$\left(\frac{m}{\rho l^3}\right)_m = \left(\frac{m}{\rho l^3}\right)_p m_p = \frac{{l_p}^3\rho_p}{{l_m}^3\rho_m}m_m = {c_l}^3c_\rho m_m \ , \tag{4}$$

$$\left(\frac{I}{l^4}\right)_m = \left(\frac{I}{l^4}\right)_p I_p = \frac{{l_p}^4}{{l_m}^4}I_m = {c_l}^4 I_m \ , \tag{5}$$

$$\left(\frac{F}{l^2E}\right)_m = \left(\frac{F}{l^2E}\right)_p F_p = \frac{{l_p}^2E_p}{{l_m}^2E_m}F_m = {c_l}^2c_E F_m \ , \tag{6}$$

$$\left(Rl\sqrt{\frac{\rho}{E}}\right)_m = \left(Rl\sqrt{\frac{\rho}{E}}\right)_p R_p = \frac{l_p}{l_m}\sqrt{\frac{\rho_pE_m}{\rho_mE_p}}R_m = c_l{c_\rho}^{\frac{1}{2}}{c_E}^{-\frac{1}{2}}R_m, \tag{7}$$

$$\left(\frac{N}{lE}\right)_m = \left(\frac{N}{lE}\right)_p N_p = \frac{l_p \rho_p}{l_m \rho_m} N_m = c_l c_E N_m \, . \tag{8}$$

In the above equations, the similarity relation of the parameters between the prototype and the model can be shown as:

$$\begin{cases} c_l = \frac{l_p}{l_m} c_I = \frac{I_p}{I_m} c_E = \frac{E_p}{E_m} c_F = \frac{F_p}{F_m} \\ \\ c_m = \frac{m_p}{m_m} c_R = \frac{R_p}{R_m} c_\rho = \frac{\rho_p}{\rho_m} c_N = \frac{N_p}{N_m} \end{cases} . \tag{9}$$

In this experiment, as long as the proportional relationship of the parameters between the model and the prototype satisfy the Equations (4)-(9), the phenomena observed in experiment was almost similar to actual drilling cases.

2. SIMULATION EXPERIMENTAL DEVICE AND EXPERIMENTAL PARAMETERS SELECTION

2.1 Simulation Experimental Device

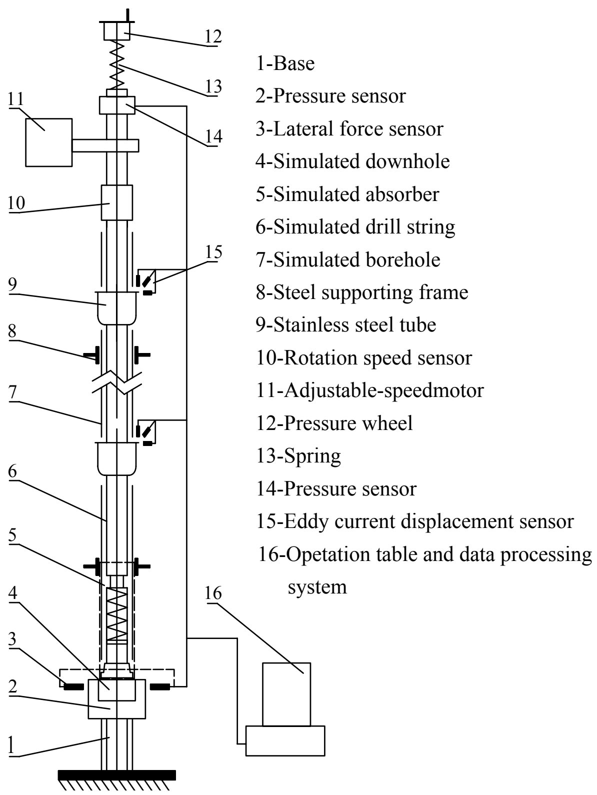

Figure 1
Total Simulated Experimental Device

Based on similarity criterion, the simulated experimental equipment [12-19] was built in 1to 10 scale penetrates (model to prototype). As shown Figure 1, the entire height of the experimental apparatus is 15 m, the height of both simulation wellbore and simulation drilling string are 13 m, and the inner diameter of simulation wellbore, there are two specifications, one is 22 mm, and the other is 31mm. The material of the drilling string model is ABS plastic which has similar stress-strain characteristics with the actual drill string. The density of ABS plastic is 1.10 g/cm^3, and elastic modulus of ABS plastic is 2.3 GPa. The measuring elements comprise measuring sensors, signal amplifiers and digital signal collectors, and the sensors include four types: eddy current displacement sensor, strain gauge drawing force transducer, strain pressure transducer and piezoelectric force transducer. By these measuring elements, experimental parameters such as longitudinal and transverse displacement of the drill string, rotation speed, hanging load and the pressure at bottom hole can be measured. The details of assembly units and specification parameters are shown in Table 3.

Table 3
Assembly Units and Specification Parameters

Unit name	Specification parameters
Simulated downhole	Outside diameter: Φ50×12,500 mm Inside diameter: Φ30/Φ25/Φ20mm optional Structure: Segmental detachable Texture of material: Unorganic glass
Simulated drill string	Outside diameter: Φ22×12,500 mm / Φ12×12,500 mm Inside diameter: Φ5 mm Structure: Segmental detachable Texture of material: Engineering plastics ABS
Eddy current displacement sensor	Probe diameter: 25 mm Nonlinear degree: 1.5%
Tension and pressure sensor	Range: 0-10 kg Accuracy: 0.05%
Rotation speed sensor	Range: 0-500 rpm Accuracy: 0.05%
Speed control apparatus	OUTput: 0-10 VDC
Industrial Personal Computer	Quad-core Q8300/ 4G/320G/ 19″indicator
Synchronous acquisition system	PCI data acquisition card: 8 channel, 250 kS/s RTSI bus Signal cable Software drivers

2.2 Election of Experimental Parameters

In order to ensure the simulated experiment is similar to actual site, the proportion relationship between the experiment parameters and actual parameters should be consistent with the similarity criterion deducted by the second section of this paper. During the derivation, while structure and material properties of the simulation drill string are determined, the proportion between model and prototype can be derived according to the similarity theory. In experiment, when the rotation speed is 2.88 times actual speed, the WOB is 1/9,130 times actual WOB and the elastic stiffness is 1/913 times actual elastic stiffness, the phenomena observed in the experiment will be similar to the actual drilling. This experiment mainly consider four influence factors speed, WOB, elastic stiffness of absorber and installation location, the proportional relationship of parameters between experiment and actual site is shown in Table 4 to Table 7.

Table 4
Experimental Speed and Actual Speed Comparison Table

No.	R_1	R_2	R_3	R_4	R_5	R_6
Model rotation speed/(r/min)	70	120	170	220	270	320
Prototype rotation speed/(r/min)	25.0	42.9	60.8	78.7	96.6	115

Table 5
Experimental WOB and Actual WOB Comparison Table

No.	w_1	w_2	w_3	w_4	w_5
Model WOB/kg	0.5	1	1.5	2	2.5
Prototype WOB/KN	44.75	89.5	134.25	179	223.75

Table 6
Experimental Elastic Stiffness and Actual Elastic Stiffness Comparison Table

No.	N_1	N_2	N_3	N_4	N_5	N_6	N_7
Model elastic stiffness /(N/mm)	0.2	0.5	1	3	5	7	9
Prototype elastic stiffness /(KN/mm)	0.18	0.45	0.91	2.74	4.66	6.39	8.22

Table 7
Installation Location in Experiment and in Actual Comparison Table

No.	L_0	L_1	L_2	L_3
Model distance/m	0	1	2	3
Prototype distance/m	0	10	20	30

3. THE MEASUREMENT OF EXPERIMENTAL PARAMETERS

3.1 Measurement of WOB at Bottom Hole

Strain gauge drawing force transducer and strain pressure transducer are used to measure bottom hole WOB which could convert the pressure signal into voltage signal. Moreover, its measurement range is 0 to 50 kilogram and sensitivity is 1.99 mV/V. Before using, the transducer should be tested in electronic universal testing machines.

3.2 Measurement of Displacement

Eddy current displacement sensors is used to measure motion of simulation drilling string in this experiment, which were installed at four different positions on steel supporting frame, in each position, three sensors were installed. And the distance between the positions and bottom hole were 1 m, 3.5 m, 5.5 m and 8 m. Through these sensors, the longitudinal and lateral motion displacement of the string could be measure under different experimental conditions. Figure 2 shows the transverse displacement measurement and Figure 3 shows the longitudinal displacement measurement.

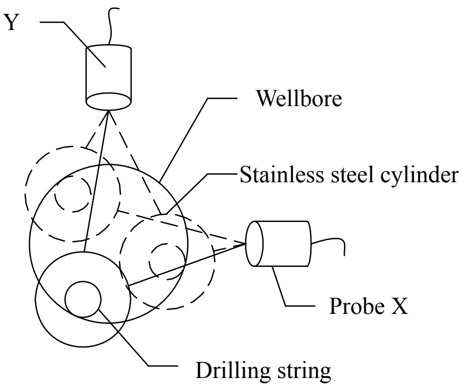

Figure 2
Transverse Displacement Measurement

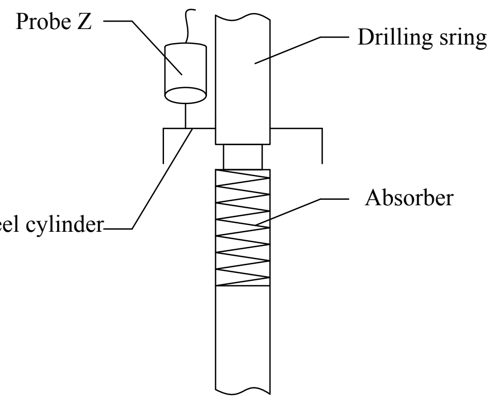

Figure 3
Longitudinal Displacement Measurement

CONCLUSION

(a) The similarity criterion deduced by the dimensional theory has a much wider applicability than which deduced by differential physical equations. In particular, to solve complex engineering problems with unclear mechanism, the dimensional theory is more reasonable and effective.

(b) Through the experiment device, the vibration of the drill string with absorber could be obviously observed and the absorber performance experiments under the conditions of different WOB, speed, installation location and elastic stiffness could be carried out.

(c) In this experiment, when the rotation speed is 2.88 times actual speed, the WOB is 1/9,130 times actual WOB and the elastic stiffness is 1/913 times actual elastic stiffness, the phenomena observed from the experiment will be similar to actual drilling. The influence rules of absorber performance obtained in test could provide support for engineering and theoretical analysis.

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