Vibration Behavior of Drilling Mechanism Based on FEM and Multibody Dynamics

Jianping Li
School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou, China
e-mail: 295002408@qq.com

Yuming Cui
School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou, China
*Corresponding author, e-mail: faithsky@yeah.net

Xinxia Cui
School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou, China
e-mail: 1365355507@qq.com

ABSTRACT
Due to the impact of coal drilling shock and drilling parameters on coupling vibration of coal auger drilling mechanism, it is difficult to predict and control vibration behaviors of drilling mechanism effectively. To explore the relationship between the vibration behaviors and drilling parameters, combined simulation of finite element method (FEM) and multibody dynamics and drilling experiment are carried out. Firstly, drilling load is determined using finite element software ANSYS LS_DYNA. Vibrations of drilling mechanism are obtained under different rotational speeds and drilling depths based on rigid-flexible coupling multibody dynamics. Drilling experiment is also conducted. The results indicate that: when \( f=2 \), drilling torque is about 912.60N·m and feed resistance is about 24.95kN; lateral vibration of drilling mechanism is minimum in the neighborhood of 60r/min in rotational speed; lateral vibration increases with drilling depth, and the vibration tends to be stable when drilling depth is 5m or longer; drilling torque and promote resistance of drilling mechanism decreases with rotational speed and increases with drilling depth.

KEYWORDS: Drilling mechanism, FEM, lateral vibration, drilling torque, drilling experiment

INTRODUCTION
Coal auger is a new type shearer for thin coal seam. It is difficult to predict and control dynamic behavior of drilling mechanism effectively due to the impact of coal cutting shock and drilling parameters on coupling vibration of drilling mechanism in coal auger. Drilling vibration in coal breaking process is one of the main ways of drilling mechanism performance deterioration. There are three main factors affecting vibration of drilling mechanism: geological conditions of coal seam, structure of drilling mechanism and drilling parameters [1]. Geological condition of
coal seam is unchangeable, and drill rod tends to be the best structure by optimizations [2-3]. Therefore, the adjustment of drilling parameters and reliable mechanisms for anti-vibration are effective measures in preventing vibration and deflection of drilling mechanism in coal auger.

By now, numerous researches have been done on the vibration characteristics of drilling system, which can be as a reference for this research. Yigit A. S. and Christoforou A. P. did theoretical studies on transverse and longitudinal coupling vibration of drill pipe in depth, and established a coupled vibration dynamic model based on Hertz contact theory [4-6]. A nonlinear dynamic inverse controlling design method was put forward by Al-Hiddabi S. A. et al. to suppress transverse and torsional coupling vibration of nonlinear drill pipe, and the damping effect was obvious [7]. Zhu Xiaohua et al. established dynamics model of bit under the interaction of drill-string, drill bit, and rock. Drill bit dynamic characteristics were obtained from simulation. And motion law and failure mechanism of drill-string are cleared [8]. Variable leading method in solving the problem of the drill-string buckling was proposed by setting different boundary conditions [9]. It was pointed out by Bairdes M. that the main reason of drilling skew is larger borehole, and the change of bit orientation is caused by larger borehole and the friction. In addition, the two contact modes, continuous contact and continuous collision, was proposed [10]. The geometrical stiffening of the drill rod using a non-linear finite element approximation was analyzed, in which large rotations and non-linear strain displacements were taken into account [11]. The nonlinear dynamic model of drilling system coupling longitudinal, transverse and torsional vibration was built to study the numerical method of high nonlinear dynamic model [12-13]. A stochastic computational model was proposed to model uncertainties in the bit-rock interaction system and the non-linear dynamical equations were discretized by displacements of the finite element method [14]. The drill rod vibrations with differential quadrature method were analyzed, which indicated the method was efficiency and accuracy in dealing with drill rod vibration problems [15]. A method of decomposing drill-string kinetics into rotary drive and axial drive was put forward in effectively drill-string vibration controlling [16]. A nonlinear dynamic model of drill rod was established to study the effects of different coal and rock hardness on transverse vibration of drill rod radius, and stabilizer was proposed to suppress the vibration [17].

Plenty of numerical theories and simulation research on longitudinal, transverse and torsional vibrations of drill rod were carried out by scholars, and lots of models were established. By now, there is few corresponding experimental research, thus, accuracy of the theories and simulations is unable to be verified. To explore the relationship between vibration characteristics of drilling mechanism and drilling parameters, simulation and experimental research on vibration of drilling mechanism was carried out under different rotational speeds and drilling depths. This study provides experimental basis in improving the stability of coal auger machine and drilling parameters adjustment.

FINITE ELEMENT MODEL AND RESULT

In order to obtain loads of drill bit in coal drilling process, coal drilling finite element model is established in ANSYS LS_DYNA, shown in Figure 1. Here, coal seam is sized of 1000×1000×1500 mm, and the material for coal is MAT_193 complied with the Mohr-Coulomb yield criterion. The tensile strength is 5.26MPa, and the compressive strength is 20.68MPa. As followed, drill bit and picks are set to be rigid, and non-reflecting boundary condition is applied onto coal surface which is fixed on ground. Then, the simulation can be started after drill bit rotational speed is set to 60 r/min, and the feed speed is 2 m/min. Coal drilling progress and drilling torque and feed resistance are shown in Figure 2 and Figure 3.
MULTIBODY DYNAMIC MODEL

Hypotheses

The vibration of drilling mechanism is very complicated because it is not only affected of gravity, cutting torque, rotational speed and feed resistance in drilling process, but also restricted by borehole wall. Hypotheses and simplifications are put forward as follows to analyze the coupling vibration of the multi-body systems in drilling mechanism expediently:

(1) The cross-section of borehole remains a rigid circular section, the axis keeps horizontal, and cross-sections of borehole under different depth are seized of the same diameter;

(2) Drill bit, gearbox and coal wall are rigid bodies, drill rods are small deformed elastomers;

(3) Deformation of drill rods is restricted by borehole wall. Random contacts and collisions emerge between drill rods and borehole wall, so as the contact reaction force;

(4) Influence of picks in drill bit and internal structures of drill rod joints and gearbox is ignored;

(5) Vibration state of drilling mechanism in cross-section is decomposed to X and Y components (X represents the horizontal component, and Y represents the vertical component).

Simulation model

Main structural parameters of drilling mechanism were obtained after simplification upon the real structure, which is shown in Table 1. Gearbox in drilling mechanism is made of Q235
steel. 16Mn steel is used in drill bit and drill rods. And performance parameters of simulation materials are shown in Table 2.

### Table 1: Main parameters of cutting mechanism

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Drill rod</th>
<th>Gearbox</th>
<th>Drill bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside diameter/mm</td>
<td>380</td>
<td>--</td>
<td>380</td>
</tr>
<tr>
<td>Inside diameter/mm</td>
<td>105</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Length or width/mm</td>
<td>1268</td>
<td>456*456</td>
<td>500</td>
</tr>
</tbody>
</table>

### Table 2: Performance parameters of simulation materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>Density (kg/m³)</th>
<th>Modulus of elasticity (GPa)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1.4×10³</td>
<td>3.5</td>
<td>0.3</td>
</tr>
<tr>
<td>16Mn steel</td>
<td>7.82×10³</td>
<td>211</td>
<td>0.29</td>
</tr>
<tr>
<td>Q235 steel</td>
<td>7.8×10³</td>
<td>210</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The rigid-flexible coupling virtual prototype of drilling mechanism was established after quality property definition, drill rod flexibility, constraints addition, contacts addition, drives and loads addition. Virtual prototype of drilling mechanism is shown in Figure 4.

![Figure 4: Multibody dynamic model of drilling mechanism](image)

In order to simulate the real motion state of drilling mechanism, “cylindrical constrain” was added into the first drill rod to allow drill rods rotate and slip along the axis only; rotary drive and slip drive were added onto “cylindrical constrain”; “fix constrain” was used to fix two drill rods; “revolute constrain” was added into joints of drill rod and gear box; and another “fix constrain” was applied to fix borehole wall and the ground. Taking the constraint effect of coal wall into account, “contact” was added between drill bit and borehole wall, and between drill rods and borehole wall. Drilling loads, shown in Figure 3, were added to the disc of drill bit.

### Numerical results

It is hard or even unable to cut coal for drill bit when rotational speed is too slow. And coal will be over crushed, wear of picks will be intensified [18], and dynamic load is too large when rotational speed is high. Therefore, simulations were carried out on drilling mechanism with 3 drill rods under rotational speed of 50r/min, 55r/min, 60r/min, 65r/min, 70r/min and slip speed of 1m/min.
Motion trajectories of measure points with 3 drill rods are shown in Figure 5. It shows that influenced by gravity and self-stiffness, drilling mechanism downwards from the first rod; and mainly moves in the lower half of borehole wall. Restricted by borehole wall, drill bit contacts and collides with the borehole wall massively and frequently.

Figure 5: Motion trajectories of measure points

Vibration statistics of measure points under different rotational speeds are obtained from the simulation results and shown in Figure 6. It suggests that the displacement transverse vibration and Standard deviation of drilling mechanism decrease firstly and then increase with rotational speed, and reach the minimum at 60r/min. Since the motion in the X direction of drilling mechanism is mainly swing around the lower half of the borehole and the motion in the Y direction is mainly bouncing caused by contacts and collisions between drilling mechanism and borehole wall, vibration of cross-sections along Y-direction is more severe than that in X-direction, but the standard deviation of vibration is opposite in X and Y direction compared with the tendency of vibration value.

Figure 6: Vibration statistics of measure points under different rotational speeds in the simulation

Simulations were carried out under rotational speed of 60r/min and slip speed of 1m/min when drilling depths are 2m, 3.4m, 4.9m, 6.4m respectively. Vibration statistics of measure points under different drilling depths were obtained and shown in Figure 5.
Figure 7: Vibration statistics of measure points under different drilling depths in the simulation

Figure 7 indicates that displacement and standard deviation of transverse vibration is increasing gradually with drill rods and the vibration growth slows down and levels off after drill rods increased to 5 m. The vibration displacement of the cross-section along Y-direction is larger than that in X-direction, but the standard deviation is the opposite in X and Y direction compared with the tendency of vibration displacement. Self-stiffness of drilling mechanism is reducing and deviator is increasing cumulatively with the increasing of drilling depth, all these led to the result shown in Figure 7.

EXPERIMENTS AND DISCUSSION

Drilling vibration test bed is consisted of three parts: power transmission system, drilling mechanism and data acquisition system. Figure 8 shows us the general diagram of test bed. And the cutting torque, the propulsive force and the transverse displacement (in X and Y directions) of drilling mechanism are required to be measured using the data acquisition system.

According to previous field experiences and experiment data [19], the compressive strength of artificial coal is approximately 2.5 times the compressive strength of natural coal. The compressive strength of artificial coal wall in this experiment is 7.94MPa, which is equivalent to the natural coal with compressive strength of 19.85MPa ($f = 2$).

Figure 8: General diagram of test bed
Impact of rotational speed

The rotational experiment was carried out on 5m long drilling mechanism under rotational speed of 50r/min, 55r/min, 60r/min, 65r/min, 70r/min and slip speed of 1m/min. Vibration curves of displacement, cutting torque and feed resistance in the experiment when $n=60r/min$ are shown in Figure 9.

![Vibration curves of displacement and cutting torque](image)

(a) Curves of displacement  (b) Curves of cutting torque and feed resistance

**Figure 9:** Vibration curves of displacements, cutting torque, feed resistance in the experiment when $n=60r/min$

Vibration statistics of measure points under different rotational speeds were obtained after statistical process on vibration data collected in the experiment, and shown in Figure 10 and Figure 11.

![Vibration statistics](image)

(a) Displacement vs rotational speed  (b) Standard deviation vs rotational speed

**Figure 10:** Vibration statistics of measure points under different rotational speeds in the experiment

![Torque and feed resistance statistics](image)

(a) Torque vs rotation speed  (b) Feed resistance vs rotation speed

**Figure 11:** Cutting torque and feed resistance statistics under different rotational speeds in the experiment
Figure 10 shows that, when rotational speed increases from 50 to 70 r/min, vibration displacement and standard deviation of drilling mechanism present the tendency of decreases firstly and then increases. And the vibration displacement and standard deviation achieve the minimum at 60 r/min. Besides, transverse vibration component in X-direction is slightly larger than component in Y-direction. As can be seen from Figure 11, cutting torque and feed resistance of drilling mechanism decrease gradually and tend to be stable when rotational speed increases from 50 r/min to 70 r/min. The Standard deviations of cutting torque and feed resistance tend to increase when rotational speed is greater than 60 r/min, and this may led to instability of the system.

Experiment results are basically consistent with simulation results, and the change of cutting torque and propulsion resistance is also consistent with the actual situation. As a consequence, it is mutual verified by experiment and simulation that the optimum rotational speed is 60 r/min. At this point, vibration of drilling mechanism reaches the minimum, where cutting torque is 350 N·m and feed resistance is 14.3 kN.

Impact of drilling depth

Experiments under different drilling depths of 2 m, 3.4 m, 4.9 m, and 6.4 m length were carried out with rotational speed of 60 r/min and slip speed of 1 m/min. Vibration statistics of measure points under different drilling depths were obtained from the experiment and shown in Figure 10 and Figure 11.

![Figure 12: Vibration statistics of measure points under different drilling depths in the experiment](image)

(a) Torque vs drilling depth  (b) Feed resistance vs drilling depth

![Figure 13: Cutting torque and feed resistance statistics under different drilling depths in the experiment](image)
According to Figure 12, transverse vibration increases gradually with drilling depth but the vibration growth rate slows down. The vibration displacement in Y-direction is much more severe than that in X-direction, but the standard deviation is opposite in X and Y direction compared with the tendency of vibration displacement. From Figure 13, cutting torque and feed resistance of drilling mechanism increases gradually with drill rods. Not liking cutting torque, feed resistance tends to be stable when drilling depth increases to 5m. Experiment results are basically consistent with simulation results, and the trend is also consistent with actual situation. As a consequence, the correctness can be mutual verified by the experiment and simulation.

**CONCLUSIONS**

1. Rigid-flexible coupling multi-body dynamics model of drilling mechanism in coal auger was established by ADAMS, and drilling cutting vibration test bed was built. Experimental and simulation researches on vibration characteristics, cutting torque and feed resistance of drilling mechanism under different rotational speeds and drilling depths were carried out.

2. Transverse vibration of drilling mechanism decreases firstly and then increases with rotational speed, and reaches the minimum near 60r/min; transverse vibration increases gradually with the increasing of drill rods and the vibration growth slows down and levels off when drilling depth increases to 5m.

3. Cutting torque and feed resistance of drilling mechanism are decreasing gradually and tend to be stable when rotational speed increases from 50r/min to 70r/min, and the Standard deviations of cutting torque and feed resistance tend to increase when rotational speed is greater than 60r/min. Cutting torque and feed resistance are increasing gradually with the increasing of drill rods. And, these may lead to instability of the system.

4. With the increasing of drilling depth, multi-assembly drilling mechanism and stabilizer can be used in vibration controlling, and closed-loop control system can effectively reduce shock and vibration of drilling mechanism in drilling process and improve the stability and reliability of whole machine.

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**REFERENCES**


