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# Experimental study on the rotation of compression-buckling rod column in a liquid-filled cylinder

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ABSTRACT

In oil drilling, the main form of movement of the bottom hole assembly is self-rotation and whirling after buckling. The rotation of a compression-buckling rotation drill string can increase the frictional force between the drill string and borehole wall, induce lateral vibration and whirl of the drill string, generate borehole wall instability and drill string damage, and even cause a drilling failure. At present, studies on the motion laws of a pressure-rotating buckling drill string are incomplete, and some are even incorrect, necessitating further improvements. In this work, the effects of axial load, rotational speed, drilling fluid, and inner diameter on the rotational motion of a compression-buckling column in a cylinder were experimentally studied. The dissipation energy before and after the transition state of the simulated drill string, from the forward whirl to self-rotation, or from the forward whirl to the backward whirl, were analysed. The results indicate the following: (1) With an increase in the axial load, a buckling drill string first experiences forward whirl. Next, both forward whirl and self-rotation occur, along with a combination of backward whirl and self-rotation along the partial vertical wall. Finally, backward whirl occurs along the wall. (2) A dynamic lubrication of the drilling fluid can reduce the forward whirl rotation amplitude of the drill string and prevent the formation of backward whirl. (3) When dynamic lubrication by the drilling fluid is improved, the borehole diameter is reduced, the hole-deviation angle increases, the critical axial load of the backward whirl increases. (4) Backward whirl may occur twice for the drill string as the axial load increases. (5) The state transition of the drill string motion conforms to the minimum dissipation power principle. The experimental results described herein can serve as a reference for studies regarding drill string dynamics and drilling practice.

## 1. Introduction

The lower part of a drill string is often in a compressive and torsional state during oil drilling, which is occasionally subjected to buckling, even plastic deformation leading to drill string damage. The studies and practices regarding drill string dynamics have proved that whirls are ubiquitous in the lower part of the drill string in a wellbore (Li, 2008; Gao et al., 1996; Shi et al., 2007a). Many measurements taken while drilling have shown that a serious whirl occurs in the bottom hole assembly (BHA), causing more damage than axial and torsional vibrations (Gao et al., 1997). Domestic and foreign scholars have carried out extensive research into the formation mechanism of a whirl. Zhang et al. established the first BHA movement simulation device in China (Zhang et al., 1988) and put forward a movement principle of a rotary drill string with backward movement as the main characteristic: when the drill string rotates clockwise about its own axis in a vertical well, the drill pipe joints or drill collars attached to the borehole wall whirl counter-clockwise around the borehole axis nearly without slide scrolling, which is in essence a multi-fulcrum self-exciting vibration. Only when the friction between the drill string and borehole wall is very small will a backward whirl of the drill string not take place. Vandiver et al. used a whirl current detection system to analyse the effects of speed on a whirl (Vandiver et al., 1990). Qu et al. analysed the whirl of a drill string using an internal and external drilling fluid, and discussed the mechanical principle and operation law of a drill string during the whirl process under such conditions (Qu and Zhang, 1994; Qu, 1994; Qu and Xu, 1997). Zhang et al. studied the relationship between the stability of a rotary drill string and the loading distance and determined that the rotation has an important effect on the stability of the drill string (Zhang et al., 2001). Chen et al. pointed out through field experiments that a whirl can significantly

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reduce the rate of penetration, and that decreases in weight on bit and bit torque both occur during a whirl (Chen et al., 2002). Guan et al. determined some movement laws of a drill string by designing BHA simulation equipment and an experimental device for achieving the rotation movement characteristics of a drill string in a horizontal well; namely, a drill string at the bottom of a horizontal well shows circular and flat eight-shaped motions at different speeds, where the motion range of the drill string at the bottom of a horizontal well is consistently at the middle or bottom of the borehole, and to the right (Guan et al., 2013a, 2013b; Shi et al., 2007b). Di et al. simplified the BHA using double stabilizers in an easily supported Jeffcott rotor model and then obtained the equivalent mass, damping, and stiffness of the model using an energy equivalent method (Di et al., 2008, 2010). Li et al. analysed the effects of the drill string material hysteresis, drill string bending deflection, turntable speed, and friction coefficient between the drill string and borehole wall, as well as the rolling friction coefficient on the drill string rotation mode. It was found that with specific drilling parameters, hysteresis might cause the drill string to frequently switch between different rotation modes, thereby affecting the safety of the drill string (Li et al., 2010). Liu et al. studied the collision and whirl problem of a drill string and borehole wall under the coupling of a drill string and drilling fluid through finite element analysis and laboratory experiments (Luo, 2009; Zhang et al., 2011; Liu et al., 2011), and found that, when the eccentricity is more than 0.8, the interfacial force of the helical flow can prevent the drill string from incurring eccentricity. Stroud et al. conducted a whirl experiment using an indoor full-sized drill string whirl simulator under different operating conditions, and pointed out that a local whirl occurs before the motion of the drill string as a whole (Stroud et al., 2011); in their research, air was used as the experimental annular drilling fluid, and the effects of other drilling fluids were not considered. Li proposed the only way to study the theory of drill string whirl, the combination of dynamic lubrication by the drilling fluid and drill string dynamics (Li, 2013) who pointed out the drill string dynamics research direction, which was the combination with drilling fluid dynamic lubrication, but the article only showed the proposed idea, without experimental verification. Li et al. pointed out that the motion and deformation state of an object (including the drill string) must meet the mechanical equilibrium principle, the principle of minimum potential energy, and the principle of minimum power dissipation rate (Li, 2016; Li et al., 2017); in addition, there is a critical rotational speed for a transition of the whirl state, and when the speed is lower than this critical value, the dissipated power increases with an increase in the rotational speed, and when the speed is higher than this critical speed, with an increase in the rotational speed, the dissipated power decreases rapidly and the deflection of the rod string suddenly decreases, and then increases (Li et al., 2017). However, only the motion law of a pressure-rotating buckling drill string under a light load was analysed, and an experimental verification of the principle of movement under a large load, such as the question of whether the drill string generating a backward whirl is in accordance with the principle of minimum power dissipation rate, was not considered. The lower part of a drill string is often in backward whirl during drilling operations, relatively few forward whirl. The backward whirl is more likely to cause the fatigue damage of the drilling tool and the early damage of the drill bit. The backward whirl of the lower part of a drill string has not been clearly understood. It is of great significance to verify that the generation of backward whirl is in accordance with the principle of minimum power dissipation rate.

In summary, although many scholars have studied the laws of a rotating drill string, such studies have not been systematic, and there are still many problems to be solved in the study of compression buckling and a rotating drill string, such as whether a backward whirl will occur when the load is increased, why the whirl disappears with an increase in the hole-deviation angle, and whether the drill string generating a backward whirl is consistent with the principle of the minimum power dissipation rate. In this study, a drill string whirl test device was designed to consider the dynamic lubrication of the drilling fluid. The effects of the load, rotational speed, drilling fluid, and inner diameter on the rotational motion of the compression-buckling column in the cylinder were studied experimentally. The dissipation energy before and after the transition state of a simulated drill string from a forward whirl to self-rotation (rotation around the axis of the pipe), or from a forward whirl to a backward whirl, was analysed.

The experimental results can provide reference for a theoretical study on whirl occurrence, and can provide theoretical guidance for the prevention of drill string damage and poor wellbore quality to reduce the drill string damage, improve the quality of the wellbore, and reduce economic loss.

## 2. Structure and principle of experimental device

### 2.1. Experimental device

Fig. 1 shows the drill string whirl simulation test device, which considers the lubrication of the drilling fluid. The device is composed of a speed-control system, an axial force loading system, a wellbore simulation system, a data acquisition system, and an imaging system. The speed-control system provides forward and backward movements at 0–3000 r·min$^{-1}$. The axial force loading system applies axial pressure to the drill string. The wellbore simulation system provides different combinations of wellbores. The data acquisition system obtains the axial force and axial displacement data through a pressure sensor, displacement sensor, acquisition card, and computer. The imaging system makes use of high-speed cameras to measure the drill string deformation and motion trajectory. The test device was originally designed to tilt; however, owing to a height limitation of the laboratory and poor operation, the device could not be tilted.

Fig. 2 shows the inclined drill string whirl simulation device, which is composed of a speed-control system, an axial force loading system, a wellbore simulation system, data acquisition system, and tilt system. The test device has the ability to test the influence of the hole-deviation angle on the drill string whirl, but does not have the capability of obtaining the whirl trajectory.

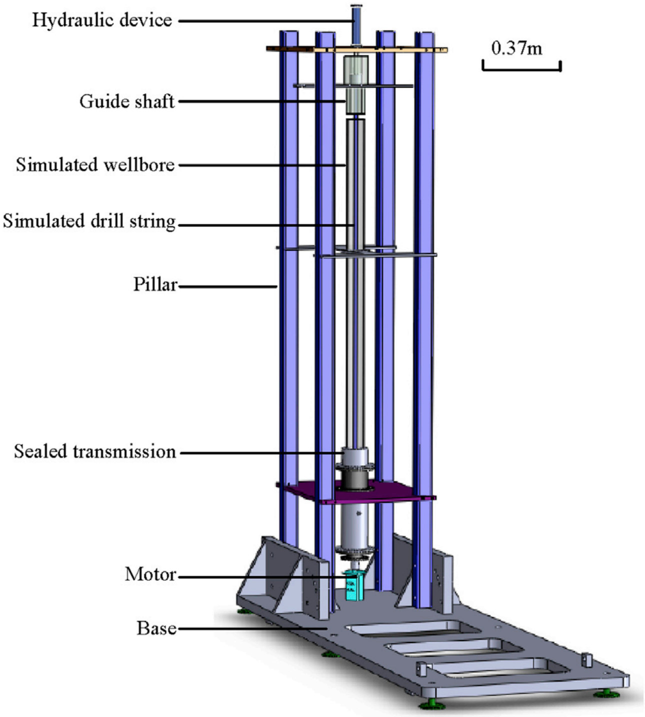

**Fig. 1.** Vertical drill string whirl simulation device.

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