Development status and application prospect of semi-active vibration reduction technology for down-hole drilling tools

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Abstract. Domestic and foreign oil companies have been constantly increasing the research and development investment in underground shock absorber, to reduce the vibration and shock of drilling tool under hard rock drilling environments, enhance the rate of penetration and decrease drilling cost under the premise of ensuring the normal life of drill string components and stable bit weight. Based on this, this paper has focused on the working principal of magneto-rheological fluid (MRF) semi-active damper, the composition of MRF and its internal parameters’ impact on the damping characteristics, combining with the status quo at home and abroad of down-hole vibration technology. Meanwhile, the test analysis of semi-active damping technology was conducted. And the results showed that semi-active vibration technology had greatly weakened the vibration level while improved the rate of penetration, guaranteed the service life of bit and other drill-string components, reduced additional tripping times and effectively solved the problems of bit weight instability and low penetration rate etc., caused by drill vibration. Therefore, in the current situation of worldwide oil price downturn, it has become increasingly prominent to reduce cost and increase efficiency, and it’s particularly necessary to research on the shock absorbers of down-hole drilling tools in China.

1. Introduction
The optimum & fast drilling technology plays an important role in the exploration and development of oil and gas resources in deep strata [1, 2], the vibration phenomenon of bottom hole assembly happens frequently in drilling operations, as exploration field expands, the lithologic hardness and other conditions of the stratum are becoming more and more complicated, the vibrations of drilling tools make the weight of bit applied to the formation unevenly, especially when resonance occurs in hard strata [3, 4, 5]. Fig.1 shows the shear failure diagram of the threaded connection of the drilling tool, which is caused by downhole vibrations.
Figure 1. The shear failure diagram of the threaded connection.

The vibration of drill string is mainly related to bit rotation, drilling mud, the unbalance of the drill string itself and so on, and the vibration types are divided into the following three types: axial vibration, radial vibration and torsional vibration. The axial vibration causes the drill bit to jump off the bottom of the well due to the severe oscillation of the bit weight, thus causing premature failure of the bit bearing and insert teeth, which affects the drilling efficiency. The radial vibration can easily lead to downhole tools colliding with wellbore, resulting in borehole enlargement, damage of drill bit and measuring instrument, which are highly destructive. And the torsional vibration tends to make the thread joint fatigue failure, and to damage the drill bit.

At present, the method of reducing bit speed and bit weight is usually adopted to suppress vibrations of drill strings at home and abroad, particularly, drill bits are usually designed for a predetermined range of rotation speed and bit weight, its performance and service life will be reduced when working under off-design conditions. However, the conventional shock absorber or vibration isolator usually isolates the upper drilling tools from the vibration, but fails to suppress the vibration of the lower drilling tools. Under this background, the semi-active vibration reduction technology based on MRF (magneto-rheological fluid) emerges as the times require [6].

2. The fundamental principle of MRF

MRF is a kind of smart material developed rapidly in recent ten years. It is usually a suspension composed of micrometer or nanometer magnetizable spherical or elliptical particles dispersed in non-magnetic liquid (mineral oil, silicon oil, etc).

It becomes a Newtonian fluid in the absence of magnetic field, which is characterized by low viscosity and good flow property, but under the applied strong magnetic field, suspended particles change from being neutral to being strong magnetic, interact with each other, and then form a chain-like bridge between the magnetic poles, thus transforming into a macroscopic columnar structure, the apparent viscosity increases by more than two orders of magnitude in a short time (milliseconds), in this way, suspension changes from liquid to visco-plastic material with the rapidly changed rheological properties, presenting mechanical properties similar to those of solids, moreover, this kind of change is continuous and reversible, and Fig. 2 shows its working principle.

Figure 2. The working principle of MRF.
MRF mainly works in the post-yield stage, and its key parameter is dynamic yield stress, which is a function of external magnetic field strength. The field application is mainly based on three working modes: flow mode, shear mode and squeeze mode, as shown in Fig.3, it possesses strong temperature stability and anti-contamination ability, and has extensive application prospects.

![Figure 3. Working modes of MRF.](image)

3. Research status of MRF semi-active vibration reduction technology
A magnetorheological damper used to attenuate drill string vibrations has been developed by the U.S. national energy technology laboratory of Deep Trek plans, the damper is mainly consisted of a MRF valve, by changing the coil current in the valve, the magnetic field strength of MRF around the coil can be adjusted to control the viscosity of MRF in the downhole environment, moreover, the viscous attenuation characteristics of MRF can be adjusted adaptively and optimally for different drilling conditions. However, the MRF valve calls for a considerable amount of electrical energy to maintain the magnetic field in the coil, which usually requires an expensive and high maintenance cost turbine generator to supply power to the coil, therefore, reducing the electrical energy required by the system under the premise of effectively suppressing drill string vibrations, especially the bit vibration, has become the main direction of MR damper development.

Scholars from Inha university in South Korea studied the influence of the shape and size of particles and the proportion of particles of different sizes in dual-particle MRF on the dynamic yield stress, sedimentary stability and damping coefficient of MRF [7]. Fig.4 shows the physical disassembly diagram of the shock absorber. By setting up the test platform of the semi-active shock absorber based on MRF, the relevant characteristics of the MRF mixed with two kinds of metal powder particles with a specific gravity of 0.67, 1.5 and 4.0 had been analyzed. Fig.5 shows response curves of three MRFs as current step changes.

![Figure 4. The physical disassembly diagram of the shock absorber.](image)

![Figure 5. Response curves of three MRFs as current step changes.](image)
Scholars from UTP university in Malaysia carried out a study on the effect of viscous damping coefficient of MRF on the overall damping stiffness of downhole drill string, and obtained the relationship between equivalent spring stiffness, viscous damping coefficient and input power. The nonlinear force-displacement characteristics and force-velocity hysteresis effects of MRF were studied by scholars from university of Ulsan in South Korea. Scholars from Sakarya university in Turkey used ANSYS finite element analysis software to optimize the geometric parameters of MRF semi-active shock absorber, and verified the correctness of theoretical simulation through experimental research. In order to study the damping force-velocity hysteresis characteristics of MRF damper under sinusoidal displacement excitation, scholars from Harbin Institute of Technology established a physical model of MRF damper in consideration of the compressibility of MRF, the simulation results show that the hysteresis width has nothing to do with the piston area, but only with the spring stiffness. Scholars from Harbin engineering university applied MRF vibration reduction technology to ship vibration isolator, which has a good effect of vibration absorption [8]. The MRF shock absorber calibration platform and force-displacement characteristic curves are shown in Fig.6. The multi-physical characteristics of the large-capacity MR shock absorber were verified by finite element simulation and experiment by Chilean scholars [9], Fig.7 shows the static magnetic field model of the MRF shock absorber, Fig.8 shows the coil distribution diagram and magnetic flux density cloud map.

With the development of the theoretical basis and experimental research on the vibration analysis of downhole drilling tools, the oil field service providers have launched their own shock absorber products. Schlumberger, for example, has introduced 12” downhole shock absorbers to reduce the axial vibration of downhole drilling tools, thus increasing the rate of penetration for rapid casing insertion of 20” and 13-3/8” in the hard formations of Kuwait's 22” and 16” boreholes. The shock absorber can reduce the...
axial alternating load generated by the interaction between drill bit and rock, improve the hole quality, prolong the life of drilling tool, and achieve the purpose of reducing cost and increasing efficiency.

The APS company has developed an active shock absorber that monitors vibration in the bottom-hole assembly (BHA) and adjusts the damping coefficient quickly to reduce vibration, and completed the first field test at the rocky mountain field test center. Test results show that the active shock absorber can improve the economic benefits of drilling in two ways: it can drop the vibration to the lowest level as well as maintain a constant drilling pressure, thus improving the efficiency of bit cutting, and it can also reduce the drill string vibration, thus avoiding to damage the drill bit and other drill string components, and meanwhile extending the drill footage and decreasing the number of additional trips. In the harder siltstone strata, the active shock absorber is more effective, but the damping effect in the softer shale is less obvious than the conventional method. Therefore, the algorithm of adjusting the damping inside the shock absorber needs to be optimized adaptively, so as to obtain the optimal rate of penetration in any strata.

4. Research status of vibration reduction technology for downhole drilling tools in China
   In China, Xiaohua Zhu established the dynamic balance equation of downhole drilling tools based on the mechanical model of downhole drilling tools and the virtual-work principle, and systematically analyzed the influence of the characteristic parameters (stiffness, location and damping) of axial shock absorber on the vibration characteristics of drill pipe and drill bit by using numerical simulation technology [10]. Furthermore, the optimal damping range of axial shock absorbers with different stiffness was determined, and the damping effect was discussed according to the interaction model between drill bit and bottom-hole rock. The analysis results have certain guiding significance to the field use and optimization design of shock absorber, to reduce downhole vibration, to improve the service life and drilling efficiency of drilling tools.

   The main factors which influencing the axial vibration were analyzed by Wenlong Wang and others who using the mathematical model of the drill string, the results show that the axial stress amplitudes appear undulating distributions along the drill string, the maximum axial stress amplitude of the drill string is roughly proportional to displacement excitation, and the curve of the maximum axial stress amplitude varying with the rotational speed seems like an upward parabola [11]. In addition, the higher the viscosity of the drilling mud, the smaller the amplitude of the maximum axial stress in the drill string. The location of the shock absorber can change the natural frequency of the drill string axial vibration system. Considering from the perspective of protecting the drill string, should be placed close to the drill bit at low rotational speed, but when it comes to high rotational speed, the shock absorber needs to be kept a certain distance from the drill bit, and it is an effective measure to prevent drill string resonance by optimizing bottom hole assembly and rotational speed.

   Domestic existing shock absorbers are mainly divided into hydraulic type and mechanical type. The maximum vibration damping force is often limited by the mechanical structure, and the matching between vibration characteristics and vibration damping is poor. Therefore, it is difficult to quickly absorb the vibration of BHA under different vibration states, and the vibration damping effect is clearly not ideal [12].

5. Conclusion
   MRF Semi-active vibration reduction technology has a wide range of damping coefficient adjustment and stronger applicability, which can better solve the problem of unstable WOB and low ROP caused by drilling tool vibration. Under the current circumstance of low oil price all over the world, the demand of reducing cost and increasing efficiency is increasingly prominent, so it is particularly necessary to study the shock absorber of downhole drilling tools.

   The damping characteristics, optimal structure design and intelligent control theory of MRF shock absorber are still to be explored. MRF semi-active vibration reduction technology with its advantages of high efficiency, intelligent and controllable will become the development direction of drilling tool vibration reduction in oil drilling, shale gas development and deep drilling at home and abroad.
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