Technological potential of impact vibration damper of drill string with discrete working medium

A V Zagulyaev¹, K A Bashmur¹, E A Petrovsky¹, V S Tynchenko¹,², N A Smirnov², V V Kukartsev¹,² and S O Kurashkin²

¹Siberian Federal University, 79, Svobodny Av., Krasnoyarsk, 660041, Russia
²Reshetnev Siberian State University of Science and Technology, 31, Krasnoyarsky Rabochy Av., Krasnoyarsk, 660037, Russia

E-mail: shura.zagulyaev@mail.ru, bashmur@bk.ru

Abstract. The article discusses issues related to vibrations of drilling string bottom layout during construction of oil and gas wells. Analysis of causes of longitudinal vibrations occurring during rotary drilling is carried out. Invention proposes using vibration dampers of impact principle of action using discrete working medium. We described a device of this type of vibration dampers for drill columns. A probabilistic model of shock vibration damper operation with discrete operating medium is given. Analysis of the model shows the efficiency of using these types of vibration dampers to eliminate high-amplitude vibrations of drill columns.

1. Introduction

The problem of vibration reduction is closely related to the increase in fatigue strength, durability and reliability of machines and mechanisms.

Often the longitudinal vibrations of the drill string (DS) are reduced to bit bounce for various reasons and with different amplitude-frequency characteristics. Often vibrations develop in hard rocks, as well as in wells with a small anti-aircraft angle [1], but the main factor of their development is the use of rolling and hybrid (combined) bits [2, 3].

The most energy-intensive type of longitudinal DS vibrations is considered to be "ground" oscillations of rolling and hybrid bits caused by the bumpness (valleys) of the face, that is, the relief resulting from the activity of the multi-ball bit [4]. Their frequency when drilling with a three-hole bit is 10 to 40 Hz when drilling with a downhole motor and 2.5 to 9 Hz when drilling with rotary drilling (or Top Drive System drilling). We note here that its amplitudes vary from 60 to 690 kN depending on drilling techniques and technologies [5]. Also we included in this category of dynamics the axial direction that can be the sharp placement of DS by the driller on the face, which is a high-amplitude blow of a bit of any kind about rock.

This type of vibration is not only one of the main causes of breakage of downhole equipment and DS with its elements, but also has a negative effect on the mechanical drilling speed, and is also a kind of vibration pump, driving the washing liquid into the downhole zone, i.e. the phenomenon of washing liquid colmatation into the productive formation [5].

The effective way is to protect the equipment with devices embedded in the DS. Application of vibration dampers balancing dynamic DS system is one of the most effective methods of passive vibration control [2].
Two types of vibration dampers are widely used in drilling.

The first devices for vibration DS damping can be above-bottom shock absorbers with elastic damping elements. These devices are not capable of damping wide range of frequencies and amplitudes of bit vibrations and are also short-lived due to relaxation properties [4].

The second species are dynamic vibration dampers, which is a secondary oscillatory system embedded in the bottom hole assembly system, oscillating in antiphase to dynamic DS movements, reducing the amplitude of its reaction. At the same time, this type of vibration dampers operates in a narrow range of excitation frequencies, so it is necessary to clearly adjust that because of dynamic excitation parameters due to, for example, rock anisotropy, it seems to be a very difficult task [6].

2. Developed DS shock damper design with discrete operating medium
Dynamic shock type vibration dampers are known which respond to a wide range of excitation [7]. A small degree of damping and inertia limit their application.

In view of these aspects, an impact vibration damper device (pat. No. RU 2533793 C1) is elaborated, in which we have tried to eliminate these shortcomings. Developed design of the impact vibration damper of floating type is presented in Figure 1.

![Figure 1. Drill string shock damper: 1 - housing; 2 – holder; 3 – groove; 4 – sphere; 5 - discrete working medium.](image)

The base of the impact vibration damper is a body of a certain mass, which collides with another element in the damping system. Often they are made in the form of balls, but bodies and other geometric shapes can be used. At the same time bodies are installed freely with a certain gap. Floating vibration dampers are adjusted to the mode of two alternating body impacts against each limiter during the period of movement, which gives the greatest effect for such devices.

To eliminate the negative effect of inertia, we added slots 3 to the shock damper, into which drilling fluid penetrates. In this way, the balls 4 are moved in a complex dispersion medium which facilitates their smooth return to their original position and increases the logarithmic discretion of
attenuation. To increase the degree of damping, we also decided to use the masses in which the discrete working medium 5 (DWM) was added. Impact vibration damper with DWM consists of mass moving along the body filled with fine particles, it provides additional energy dissipation inside the working ball or other working element [8]. It is also possible that in the impact vibration damper the DWM can be dispersed over the internal space of the housing [9]. However, in this case, the chaotic movement of masses is difficult to control and mechanical wear of the vibration damper body is possible.

DWM is a mechanical system that is a collection of individual particles, each of which, taken separately, has all the properties of a solid. Generally, the term DWM applies to physical bodies intermediate solids and liquids. Such bodies are called loose bodies. The adhesion forces between the individual particles of the system are absent at all or very small. As a result, loose bodies do not perceive tensile forces, this sharply distinguishes them from solid bodies. As a rule, they are granules, balls or some fine medium, for example, sand [9].

3. Probabilistic model of energy dissipation in impact vibration damper with DWM

The calculation will be based on the fact that the DWM particles are quite small compared to the size of the ball in which they are placed. Their movement in this case will depend on many factors. In addition to longitudinal oscillations, there may be a component of transverse oscillations, torsional and other type of disturbances, it is more appropriate to consider the probabilistic model of movement of DWM particles in the ball.

We suppose that particles in this volume move randomly, periodically (in proportion to the period of oscillation of the system itself) collide with each other and change both the direction of speed and its modulus.

Let $f(\bar{v})$ be a function of particle distribution density in any velocity direction. Then the $dP$ probability of detecting a particle at a rate taking a value from a $\bar{v}$ range of to $\bar{v}+d\bar{v}$ is proportional to the volume in the velocity space within which the velocity vector can be depicted in the following way:

$$dP = f(\bar{v})dV.$$  \hfill (1)

The length of the velocity interval $d\bar{v}$ is infinitely small, so the velocity of particles falling within the interval $[\bar{v};\bar{v}+d\bar{v}]$ and in magnitude and in direction differ slightly. In this sense, it can be said that $f(\bar{v})$ is a function of the density of the particle distribution by velocity in a given direction.

In the Cartesian coordinate system, the velocity vector $\bar{v}$ is uniquely determined through its projections $v_x, v_y, v_z$. In particle collisions between each other, each velocity projection varies independently, in accordance with the law of momentum preservation. Therefore, the velocity projections on an arbitrarily selected Cartesian coordinate system are independent random quantities. The probability $dP_x$ that the $x$-component of the particle velocity takes a value from the range of $v_x$ to $dv_x$ is:

$$dP_x = \varphi(v_x)dv_x.$$  \hfill (2)

Similarly $y$ and $z$ – the velocity component. We assume that all directions of movement of particles in the ball are equal. Therefore, the three velocity projections are equal to the overvaluation and are described by the same functions of the distribution density $\varphi$. Then the probability that all three independent velocity components take values at specified intervals simultaneously is calculated as the product of probabilities:

$$dP = dP_xdP_ydP_z$$  \hfill (3)

or

$$f(\bar{v})dV = \varphi(v_x)\varphi(v_y)\varphi(v_z)dv_xdv_ydv_z.$$  \hfill (4)

At the same time:
\[ f(\vec{v}) = \phi(v_x) \phi(v_y) \phi(v_z). \]  

We take the logarithm of expression (5):

\[ \ln f(\vec{v}) = \ln \phi(v_x) + \ln \phi(v_y) + \ln \phi(v_z). \]  

Function arguments on the right and left in this equation are related by:

\[ v^2 = v_x^2 + v_y^2 + v_z^2. \]  

Consequently, these two equations should be solved together:

\[ \begin{cases} 
\ln f(\vec{v}) = \ln(v_x) + \ln(v_y) + \ln(v_z); \\
v^2 = v_x^2 + v_y^2 + v_z^2. 
\end{cases} \]  

Independent variables \( v_x, v_y, v_z \). We will create both equations on one of them:

\[ \begin{cases} 
\frac{f'(\vec{v})}{f(\vec{v})} \frac{\partial v}{\partial v_x} = \phi(v_x); \\
\frac{f'(\vec{v})}{f(\vec{v})} \frac{\partial v}{\partial v_y} = \phi(v_y); \\
\frac{v}{v_x} \frac{\partial v}{\partial v_z} = v_z. 
\end{cases} \]  

In this case:

\[ \frac{1}{v} \frac{f'(\vec{v})}{f(\vec{v})} = \frac{\phi(v_x)}{v_x \phi(v_x)}. \]  

By doing the same for the rest of the speed components, we get:

\[ \frac{1}{v_x} \frac{\phi(v_x)}{\phi(v_x)} = \frac{1}{v_y} \frac{\phi(v_y)}{\phi(v_y)} = \frac{1}{v_z} \frac{\phi(v_z)}{\phi(v_z)}. \]  

Each fraction contains functions of only one variable. Variables \( v_x, v_y, v_z \) are independent, and functions from different independent variables match at any value of variables only if they are equal constants. We denote this constant through \(-2a\), then:

\[ \frac{1}{v_x} \frac{\phi(v_x)}{\phi(v_x)} = -2a; \frac{1}{v_y} \frac{\phi(v_y)}{\phi(v_y)} = -2a; \frac{1}{v_z} \frac{\phi(v_z)}{\phi(v_z)} = -2a. \]  

A differential equation was obtained for the function of the density of the particle distribution over one of the Cartesian velocity components. Solving it, we will receive:

\[ \phi(v_x) = A \exp(-av_x^2) \]  

where \( A \) – normalization factor. It is in condition:

\[ \int_{-\infty}^{\infty} \phi(v_x) dv_x = A \int_{-\infty}^{\infty} \exp(-av_x^2) dv_x = 1. \]  

The value of the integral is \( \sqrt{\pi/a} \), therefore \( A = \sqrt{a/\pi} \). In order to determine the constant \( a \) we assume that one degree of freedom, for example, the X-axis, is energy \( m\vec{v}^2/2 \), where \( \vec{v} \) is the speed of the ball at the initial moment of time, \( m \) is the mass of one particle. This energy corresponds to the average kinetic energy of the motion of the particles. In this case:

\[ \left\langle \frac{mv_x^2}{2} \right\rangle = \int_{-\infty}^{\infty} \frac{mv_x^2}{2} \phi(v_x) dv_x = \frac{m}{2} \sqrt{a \frac{\pi}{4a}} \int_{-\infty}^{\infty} v_x^2 \exp(-av_x^2) dv_x \]  

but integral:

\[ \int_{-\infty}^{\infty} v_x^2 \exp(-av_x^2) dv_x = \left(\frac{\pi}{4a}\right)^{1/2}. \]  

That is why:
\[ \frac{m}{2} \left( \frac{a}{\pi} \right)^{1/2} \left( \frac{\pi}{4a} \right)^{1/2} = \frac{m\bar{v}^2}{6} ; \]  

so:

\[ a = \frac{3}{2\bar{v}^2} . \]  

Distribution density per component function:

\[ \phi(v_x) = \left( \frac{3}{2\pi\bar{v}^2} \right)^{1/2} \exp \left( -\frac{3v_x^2}{2\bar{v}^2} \right) . \]  

Distribution density function for any velocity direction:

\[ f(\vec{v}) = \left( \frac{3}{2\pi\bar{v}^2} \right)^{3/2} \exp \left( -\frac{3\vec{v}^2}{2\bar{v}^2} \right) . \]  

Its mathematical expectation will be the average velocity of the particles. By dropping elementary statements, we will get:

\[ \langle \vec{v} \rangle = \left( \frac{3\bar{v}^2}{3\pi} \right)^{1/2} \approx 0.92\bar{v} . \]  

This is the velocity of the particles for any direction, and therefore for the direction of movement of the ball. Thus, the particles "push" it even further after the fall of the ball, increasing its speed by the above amount.

In connection with this the speeds of balls after impacts will change. Values of speeds after impact of balls are given in Table 1.

| Ball number (n) | Speed after impact, m/s |
|----------------|------------------------|
| 2              | 20.4                   |
| 3              | 13                     |
| 4              | 7.8                    |
| 5              | 6.1                    |

By approximating this data using the least squares method, we get a dependency:

\[ u(n) = 45.021e^{-0.413n} . \]  

We take the masses of the first five balls 0.05, 0.1, 0.15, 0.2 and 0.25 kg. It should be taken into account that the mass of the ball will become larger due to the addition of the DWM. If sand is taken as the DWM, then with optimal filling of the cavity (by 50% of its volume), the mass of the ball will increase by about 0.5 kg, which means the mass of the balls will have an approximation:

\[ m(n) = 2n - 1.1 . \]  

The energy supplied to the vibration damper went to the kinetic energy of the initial take-off of the balls:

\[ W = \sum_{i=1}^{n} \frac{m_i v_i^2}{2} . \]  

The share of dissipated energy will be found as:

\[ \alpha = \frac{W}{W_n} . \]  

Acting further according to [10] that equality (25) will take the form:
\[ \alpha = \frac{\sum_{i=1}^{n} (2i-1.1)(45.021\exp(-0.413i))^2}{\sum_{i=1}^{n} 100 \cdot \sum_{i=1}^{n} 2i-1.1}. \]  

(26)

Graphic interpretation (26) is shown in Figure 2.

Figure 2. Graph of the ratio of dissipation energy using DWM depending on the number of balls

From the graph in Figure 2, it can be seen that the share of dissipated energy grows as the used balls increase. The maximum is achieved when using 9 balls. Then the energy dissipation coefficient begins to decrease, which is caused by low efficiency of use of balls with large mass and dimensions. This is due to the reduction in the time required to move the ball and the DWM particles therein, which reduces the number of collisions.

4. Conclusion

The most energy-intensive type of the longitudinal vibration drill string (DS) is considered to be oscillations caused by the relief of the well face resulting from the operation of a multi-bit or hybrid bit. For their damping there are 2 main types of vibration dampers: overhead shock absorbers and dynamic vibration dampers. Both types have significant disadvantages, particularly the narrow range of DS vibration damping. Dynamic vibration dampers of impact type are apart.

We described a device devoid of these disadvantages. In it, working elements are filled with discrete working medium and are lubricated with drilling fluid. This reduces the inertia of the vibration damper and the degree of damping. A probabilistic model of this vibration damper has been developed, which shows that the impact vibration damper performs its function in full. The proportion of dissipated vibration energy increases as the number of balls used increases to nine, and then begins to fall, as the speeds of the upper heavy balls after impact become smaller up and the useful energy stops growing.

References

[1] Chin W C 1994 Wave Propagation in Petroleum Engineering: Modern Applications to Drillstring Vibrations, Measurement-While-Drilling, Swab-Surge, and Geophysics (Gulf Pub. Co.)
[2] Dong G and Chen P 2016 Shock Vib. 2016 7418635
[3] Mitchell R F and Allen M B 1987 Proc. of the SPE Annual Technical Conf. and Exhibition (Dallas, TX, USA) pp 237–50
[4] Yunin E K 1983 Low-Frequency Oscillations of a Drill Bit (Moscow: Nedra)
[5] Yanturin A Sh 1987 Oil Industry [in Russian – Neftyanoe khozyaystvo] 12 20–3
[6] Petrovsky E A et al 2019 J. Phys.: Conf. Ser. 1353 012098
[7] Ibrahim R A 2009 Vibro-Impact Dynamics (Heidelberg: Springer-Verlag Berlin)
[8] Lu Z, Lu X and Masri S F 2010 J. Sound Vib. 329 5415–33
[9] Lu Z, Wang Z, Masri S F and Lu X 2018 Struct. Control Health Monit. 25(1) e2058
[10] Petrovsky E A, Bashmur K A and Nashivanov I S 2018 Construction of Oil and Gas Wells on Land and Sea [in Russian – Stroitel'stvo neftyanyh i gazovyh skvazhin na sushe i na more] 2 9–14