INTRODUCTION

With the increasing exploration of deep oil and gas resources, as well as the unconventional resources, like shale gas, tight oil, and gas hydrate, the downhole situation becomes more complex in the drilling stage. In order to prevent the accidents such as sticking, trajectory drift, drilling fluid leakage, blowout, and hole deviation, it is important to transmit downhole information to the surface quickly and in real time. Accompanied by this trend, the acoustic technology is developed to transmit downhole information. This technology takes acoustic wave as information carrier and uses drill string as transmission channel. The corresponding transmission process is independent of drilling fluid and not restricted by formation properties. Moreover, the structure of transmission instrument is simple and it is easy to launch directionally. Therefore, many researchers and companies devote to study downhole information acoustic transmission technology. Many companies have started the preliminary application of the technology, such as the acoustic telemetry system from Halliburton and the wireless while drilling measurement system from Schlumberger. The maximum transmission depth and rate reaches 3600 m and 33 bit/s, which...
shows a good application prospects. At the same time, technologies related to acoustic wave transmission are also used in other fields, like stratified water injection, sand production monitoring, and cluster wells anticolision.

The drill string, as the transmission channel of downhole acoustic information, consists of drill pipes. Available study found that the frequency spectrum shows the characteristics of comb filter when acoustic wave propagates in periodic drill string. The passband with smaller attenuation and the stopband with larger attenuation alternately appear in the spectrum. Therefore, the selection of acoustic carrier frequency is very important, and the unsuitable carrier frequency will cause poor transmission quality, short transmission distance, and even interruption of transmission of acoustic signals.

During field drilling process, the loading of the drill string is complex. The drill string rotates in the hole full of drilling fluid and bears the loads of pulling, pressing, bending, and twisting. In most cases of well bore conditions, the drill string is under tension condition caused by axial force. Field tests have revealed that axial force has impact on acoustic frequency spectrum characteristics in drill string. Therefore, it is necessary to analyze the characteristics of acoustic spectrum in drill string under tension to optimize and promote the field application of downhole information acoustic transmission technology.

In this study, we experimentally investigated the impact of axial force on acoustic frequency spectrum characteristics in drill string. Furthermore, we proposed a multilevel evaluation method based on the improved radar chart to evaluate the experimental results. By this method, the evaluation criteria of acoustic spectrum in drill string under tension were established. The criteria can distinguish the impact of different axial forces on acoustic spectrum characteristics.

2 THEORETICAL BACKGROUND

The implementation process of acoustic telemetry technology includes three processes: generation, transmission, and reception of acoustic signals. Firstly, the downhole information such as well deviation and azimuth is measured by the sensor and the signals are transmitted to the acoustic generator. The signals are converted into acoustic waves by the transducer and transmitted upward through the drill string. Secondly, the acoustic waves are transmitted to the wellhead receiving device through repeaters located in drill string. Finally, the acoustic waves are detected and converted into electrical signals by receiving device, and then, the signals are processed and analyzed. Therefore, drill string plays an important role during the transmission process.

The drill string is composed of unified standard pipes and couplings. As shown in Figure 1, the direction along the pipe is denoted by the variable $x$. The time interval is denoted by $t$, and Young’s modulus and unit weight are denoted as $E$ and $\gamma_v$, respectively. The attributes of each element are constant and denoted with the subscript $\xi = 1, 2$, where the numbers 1 and 2 represent the pipe and coupling, respectively. The outer diameter and cross-sectional area of each element are indicated by $d_\xi$, $s_\xi$, respectively. The density and acoustic velocity of each element is denoted by $\rho_\xi$, $c_\xi$, respectively. The cross-sectional area of each element is denoted by $s_\xi$. The acoustic dispersion equation is given by:

$$\cos kl = \cos \frac{\omega l_1}{c_1} \cos \frac{\omega l_2}{c_2} - \frac{1}{2} \left[ \frac{\xi_1}{\xi_2} + \frac{\xi_2}{\xi_1} \right] \sin \frac{\omega l_1}{c_1} \sin \frac{\omega l_2}{c_2}$$ (1)

The wave equation of longitudinal wave is given by:

$$\frac{\partial^2 u}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 u}{\partial t^2}$$ (2)

The acoustic dispersion equation and wave equation drill string are established under the balance of gravity and other forces, and the length and cross-sectional area of pipe and coupling are important factors of acoustic propagation characteristics. These parameters will change after elastic deformation of drill string caused by axial force. Therefore, the change of the corresponding parameters caused by axial force should be considered in the analysis of acoustic frequency spectrum characteristics in drill string under tension.

Assuming that the material is homogeneous and continuous, and the small disturbance caused by acoustic wave superimposed on the static finite deformation of drill string, and the material is hyperelastic, the temperature is constant during deformation. Poisson’s ratio of drill string is denoted as $\mu$. In the range of linear elastic, the length and cross-sectional area of pipes and couplings under tension condition can be expressed as:

$$l'_1 = \left(1 + \frac{F_x}{E s_1}\right) l_1; l'_2 = \left(1 + \frac{F_x}{E s_2}\right) l_2;$$

$$d'_1 = \left(1 - \mu \frac{F_x}{E s_1}\right) d_1; d'_2 = \left(1 - \mu \frac{F_x}{E s_2}\right) d_2$$

where $F_x$ is the axial force in the drill string at position $x$. During field drilling, the axial force in drill string is complex and changes with the position, and only the constant axial force is considered in this model.

The acoustic dispersion equation can be rewritten as:

$$\cos kl' = \cos \frac{\omega l'_1}{c_1} \cos \frac{\omega l'_2}{c_2} - \frac{1}{2} \left[ \frac{\xi'_1}{\xi'_2} + \frac{\xi'_2}{\xi'_1} \right] \sin \frac{\omega l'_1}{c_1} \sin \frac{\omega l'_2}{c_2}$$ (4)

The displacement, $u(x, t)$, can be obtained from Equation (2) as below:
where $z$ is the acoustic impedance, defined as $z = \rho sc$. $\omega$ is the angular frequency, defined as $\omega = 2\pi f$, of which $f$ is the frequency. The normal components of the displacements of incident and reflected waves are denoted by $u_t$, $u_r$, respectively, and where $k$ and $j$ represent the wave number and imaginary unit, respectively.

The axial force caused by acoustic wave on the cross-section of drill string can be calculated as below:

$$F = -\rho sc^2 \frac{\partial u}{\partial x} = -jk\rho sc^2 (u_t e^{jkx} - u_r e^{-jkx}) e^{jot} \quad (6)$$

The continuity of displacement normal component and normal force is the equilibrium conditions for acoustic wave passing through the interface between the pipe and coupling. Assuming that both ends of drill string are absorbing boundaries, the equilibrium equation can be established as below:

At the position $x = -l_2/2$.

$$\left( u_t e^{jkx} + u_r e^{-jkx} \right) e^{jot} = \left( u_{t1} e^{jkx} + u_{r1} e^{-jkx} \right) e^{jot} \quad (7)$$

$$-jk\rho s c^2 \left( u_{t1} e^{jkx} - u_{r1} e^{-jkx} \right) e^{jot} = -jk\rho s c^2 \left( u_{t2} e^{jkx} - u_{r2} e^{-jkx} \right) e^{jot}$$

At the position $x = l_2/2$.

$$\left( u_t e^{jkx} + u_r e^{-jkx} \right) e^{jot} = \left( u_{t2} e^{jkx} + u_{r2} e^{-jkx} \right) e^{jot} \quad (8)$$

$$-jk\rho s c^2 \left( u_{t2} e^{jkx} - u_{r2} e^{-jkx} \right) e^{jot} = -jk\rho s c^2 \left( u_{t3} e^{jkx} - u_{r3} e^{-jkx} \right) e^{jot}$$

Combining Equation (7) and Equation (8), the recurrence relation can be obtained as below:

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} u_{t1} \\ u_{r1} \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} u_{t3} \\ u_{r3} \end{bmatrix} \quad (9)$$

For the $n$th analysis unit, the transfer matrix of displacement amplitude can be expressed as:

$$\prod_{n=1}^{N} \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} u_{t1} \\ u_{r1} \end{bmatrix} = \begin{bmatrix} u_{tn} \\ u_{rn} \end{bmatrix} \quad (10)$$

which can be rewritten as:

$$\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} u_{t1} \\ u_{r1} \end{bmatrix} = \begin{bmatrix} u_{tn} \\ u_{rn} \end{bmatrix} \quad (11)$$

where

$$M_{11} = \prod_{n=1}^{N} m_{11}, \quad M_{12} = \prod_{n=1}^{N} m_{12}, \quad M_{21} = \prod_{n=1}^{N} m_{21}, \quad M_{22} = \prod_{n=1}^{N} m_{22}$$

According to the definition of equivalent transmission and reflection coefficients, $t_N = u_{tn}/u_{t1}$ and $r = u_{rn}/u_{r1}$ are defined as transmission and reflection coefficients, respectively. Assuming infinite length at right end of drill string, which means that there is no reflected wave at the end ($u_{rn} = 0$).

The spectrum characteristic analysis equation can be established based on the acoustically transparent layers theory. According to the equation and transfer matrix method, the relationship equation between the transmission and reflection coefficients of acoustic wave at different interfaces can be obtained as follows:

$$\begin{bmatrix} t_N \\ 0 \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} 1 \\ r \end{bmatrix} \quad (13)$$

The transmission coefficient is given by:

$$t_N = M_{11} - \frac{M_{12} M_{21}}{M_{22}} \quad (14)$$

Equation (14) is the analysis model for calculating the transmission coefficient of acoustic wave in the periodic drill string.
string under tension condition, which is established based on the transfer matrix method.

The following parameters were used to design the periodic pipe model, as listed in Table 1. Using Equations (4) and (14), the frequency ranges corresponding to the passbands and stopbands can be calculated. The dispersion map and spectrogram of acoustic wave transmitted inside the periodic drill string under the constant axial stress 0 MPa and 170 MPa are shown in Figures 2 and 3, respectively. We note that the drill string channel shows unique spectrum characteristics, and the corresponding frequency spectrum exhibits the characteristics of comb filter. The passband has attenuation and distortion while stopband has larger attenuation and distortion in the spectrum. The passband and stopband alternately appear. Although many passbands exist in the spectrum, there are serious fluctuations in the amplitude-frequency characteristics and obvious differences in the passband width as well as attenuation. Thus, it can be seen that the drill string channel is an unstable wireless channel and the full mastery of channel characteristics is the premise of using drill string to transmit acoustic signals.

3 | EXPERIMENTAL STUDY

3.1 | Experimental apparatus and procedure

The acoustic propagation characteristic tests in drill string under various tension conditions were conducted using the acoustic telemetry apparatus, as shown in Figure 4. It consists of a signal generating unit, a drill string unit, a loads exerting unit, and a signal receiving and processing unit. The signal generating unit is composed of an acoustic transducer and an arbitrary wave generator. The drill string unit consists of six drill pipes of the same size, as shown in Figure 5. The loads exerting unit is composed of lifting jack and pressure monitor, and the axial force applied in the drill string ranges from 0 to 220 kN, which is within the tensile strength of the test apparatus. The signal receiving and processing unit consists of accelerometer, signal conditioner, oscilloscope, and computer.

The procedures of acoustic propagation characteristics test under different tension process can be mainly divided into the three stages, as follows:

1. Installation of telemetry apparatus stage: Firstly, six drill pipes were connected into drill string, and acoustic transducer and acceleration sensor were installed in corresponding position in drill string. Then, the loads exerting unit was installed on the drill string, and sound insulation materials were installed at the contact positions of these units. Finally, arbitrary wave generator, oscilloscope, computer, and other instruments were installed.

2. Acoustic characteristics testing stage: Firstly, low-frequency pulse waves were generated by arbitrary wave generator, and the excitation voltage, pulse width, and rate of low-frequency pulse were set to 10 V, 1 μs and 1 Hz, respectively. The acoustic signals were recorded by the signal receiving and processing unit every 20 kN increase of axial force.

3. Acoustic signals processing stage: Firstly, the frequency spectrum of acoustic waves in drill string under different axial forces was obtained by fast Fourier transformation of time domain signals. Secondly, the acoustic spectrograms were plotted by using frequency as x-axis and the amplitude as y-axis, and then the spectrum characteristics were analyzed.

![FIGURE 2](image1)  Acoustic dispersion curves

![FIGURE 3](image2)  Transmission coefficient spectrum

| TABLE 1 | Periodic pipeline parameters |
|---|---|---|---|---|
| Pipelines | \( l \) (m) | \( \rho \) (kg/m³) | \( c \) (m/s) | \( s \) (cm²) |
| Pipe | 8.69 | 7870 | 5050 | 24.52 |
| Tool joint | 0.46 | 7870 | 5050 | 130.0 |
3.2 | Experimental results

Figure 6 shows the acoustic frequency spectrum in the drill string without axial force. We note that passbands and stopbands are alternately generated in the frequency range 0-10 kHz inside periodic drill string, and there are three passbands in the spectrogram.

According to the basic technology principle of the noncontinuous orthogonal frequency division multiplexing, a widely studied digital modulation technology for data while drilling, we know that its carrier intervals are selected within several noncontinuous passbands in the spectrum, and there are multiple continuous subcarriers, including pilot signals in each carrier interval. Thus, the spectrum stability in drill string channel is the premise of transmitting acoustic signals by drill string.

However, from Figure 7, the acoustic frequency spectrum in the drill string under different axial stresses, we observe that the spectrum characteristics change with the changes of axial forces. These changes manifest in the position, width, and attenuation of different passbands, and the extent of changes is distinct to different passbands.

The axial force in drill string seriously affects the acoustic wave propagation characteristics in drill string and results in poor stability, shorter transmission distance, discontinuous transmission process. Therefore, it is necessary to evaluate the propagation characteristics of acoustic wave in drill string under different axial forces. Especially,
the acoustic frequency spectrum in drill string should be evaluated.

4  |  EVALUATION

The acoustic spectrum characteristics are determined by all passband characteristics in the spectrum while the characteristics of different passbands are determined by multiple indicators in the passband. Therefore, the evaluation is a complex process, which requires multilevel and comprehensive evaluation.

4.1  |  Evaluation method

Radar chart method is one of the effective means for multi-indicators comprehensive evaluation, and the traditional radar chart method and improved radar chart method are in common use.30,31 Although the traditional radar chart is intuitive and simple to draw, there are some obvious disadvantages. First, it does not consider the weight differences between evaluation indicators. Second, the nonuniqueness of the evaluation results will be caused by the different radar chart shape when indicators are arranged differently. Therefore, an improved radar chart method is proposed as the evaluation measure in this paper. The corresponding analysis process mainly includes the following steps: Firstly, the unit circle is divided into n sectors according to the selected n indicators and each sector region is used as the indicator corresponding domain. The central angles of different sectors are used to represent the weights of corresponding evaluation indicators. Secondly, take the sector radius as the axis and calibrate the standardized quantitative value of indicators on corresponding indicator axis. Thirdly, the calibration value is used as the radius and determines the center angle by the weight to draw the circular arc to obtain the radar chart. Finally, the evaluation results are calculated by using the eigenvectors constructed by the area and perimeter of radar chart.32-34

4.1.1  |  Constructing eigenvector

The eigenvector, \( \mathbf{u}_j \), is given by \( \mathbf{u}_j = [S_j, L_j] \). Supposing that there are n schemes to be evaluated, and the \( i \)th scheme has \( k \) evaluation indicators, the area and perimeter of radar chart are denoted as \( S_i \) and \( L_i \), respectively. \( n_{ij} \) is the standardized value of the indicator value of item \( j \). The constructed eigenvector is given by:

\[
S_i = \pi \left( \frac{\theta_{i1}}{360} n_{i1}^2 + \frac{\theta_{i2}}{360} n_{i2}^2 + \cdots + \frac{\theta_{ik}}{360} n_{ik}^2 \right)
\]

\[
L_i = 2\pi \left( \frac{\theta_{i1}}{360} n_{i1} + \frac{\theta_{i2}}{360} n_{i2} + \cdots + \frac{\theta_{ik}}{360} n_{ik} \right)
\]

\((i = 1, 2 \cdots n; k = 2, 3 \cdots)\)

where \( S_i \) and \( L_i \) represent the overall advantage of the evaluation object and the balance of the changes of each evaluation indicator, respectively.

4.1.2  |  Constructing evaluation vector

According to the constructed eigenvector, the evaluation vector, \( \mathbf{v}_i \), is given by \( \mathbf{v}_i = [v_{i1}, v_{i2}] \). It is defined as:

\[
v_{i1} = \frac{S_i}{S_m}
\]

\[
v_{i2} = L_i / \left( 2\pi \sqrt{S_i / \pi} \right)
\]

\((16)\)

\[
S_m = \max (S)
\]

\[
v_{ij} \in [0, 1]
\]

where \( v_{i1} \) represents the area evaluation value, which characterize the comprehensive level of the evaluation object, and \( v_{i2} \) represents the perimeter evaluation value, which characterize equilibrium of the indicator changes of the evaluation object.

4.1.3  |  Constructing evaluation function

According to the constructed eigenvector, the evaluation function \( f(v_{i1}, v_{i2}) \) is constructed by geometric mean method, which is defined as:

\[
f(v_{i1}, v_{i2}) = \sqrt{v_{i1}v_{i2}}
\]

\((17)\)

4.1.4  |  Selection and standardization of evaluation indicators

According to the characteristics of acoustic spectrum in drill string and the principle of signal modulation, five indicators, including lower frequency, bandwidth, peak value, peak-corresponding frequency and energy, are selected as the evaluation indicators of passband characteristics. And in the evaluation process, the effect of each indicator on passband can be approximately regarded as equal. Therefore, the weight of each indicator is considered equal, which means the angle between the axes of each indicator in radar chart is 72 degrees.

As shown in Figure 8, the upper frequency determines the position of passband, whose stability has a remarkable impact on the carrier frequency and the transmission quality of acoustic signals. The bandwidth determines the carrier frequency range, which determines the coding form of signal modulation technologies. The peak value and peak-corresponding frequency reflect the characteristics of the optimal carrier band. The energy calculated by integral of curve to x-axis within passband determines the signal intensity.
Supposing that there are \( n \) passbands in the spectrum, the standardization process of the evaluation indicator data in the \( i \)th passband is as follows:

1. Lower frequency \( K_{ifn} \)

\[
K_{ifn} = 1 - \frac{f_{iLn} - f_{iL0}}{f_{iL0}}
\]  

(18)

where \( K_{ifn} \) represents the standardized value of the lower frequency of the \( i \)th passband in the spectrogram under \( n \) MPa axial tension, \( f_{iL0} \) and \( f_{iLn} \) represent the lower frequency values of the \( i \)th passband in the spectrogram under 0 MPa and \( n \) MPa axial tension, respectively.

2. Bandwidth

\[
K_{iWn} = 1 + \frac{W_{in} - W_{00}}{W_{00}}
\]  

(19)

where \( K_{iWn} \) represents the standardized value of the bandwidth of the \( i \)th passband in the spectrogram under \( n \) MPa axial tension, \( W_{00} \) and \( W_{in} \) represent the bandwidth values of

**Figure 7** Acoustic frequency spectrum in drill string under different axial tensile stresses
the \(i\)th passband in the spectrogram under 0 MPa and \(n\) MPa axial tension, respectively.

3. Peak value

\[ K_{ipn} = 1 - \frac{P_{in} - P_{i0}}{P_{i0}} \]  

(20)

where \(K_{ipn}\) represents the standardized value of the peak value of the \(i\)th passband in the spectrogram under \(n\) MPa axial tension, \(P_{i0}\) and \(P_{in}\) represent the peak values of the \(i\)th passband in the spectrogram under 0 MPa and \(n\) MPa axial tension, respectively.

4. Peak-corresponding frequency

\[ K_{ifpn} = 1 - \frac{f_{ipn} - f_{i0}}{f_{i0}} \]  

(21)

where \(K_{ifpn}\) represents the standardized value of the peak-corresponding frequency of the \(i\)th passband in the spectrogram under \(n\) MPa axial tension, \(f_{i0}\) and \(f_{ipn}\) represent the peak-corresponding frequency values of the \(i\)th passband in the spectrogram under 0 MPa and \(n\) MPa axial tension, respectively.

5. Energy

\[ K_{ien} = 1 + \frac{E_{in} - E_{i0}}{E_{i0}} \]  

(22)

where \(K_{ien}\) represents the standardized value of the energy of the \(i\)th passband in the spectrogram under \(n\) MPa axial tension, \(E_{in}\) and \(E_{i0}\) represent the energy values of the \(i\)th passband in the spectrogram under 0 MPa and \(n\) MPa axial tension, respectively.

The passband evaluation value is defined as the function calculated by the corresponding evaluation indicators. Supposing that there are \(n\) passbands in the spectrum, the characteristic values of \(n\) passbands are taken as \(n\) indicators to evaluate the spectrum characteristics. Their weights are determined by the passband energy proportion of each initial passband. The center angle of the indicator axis in the improved radar chart is calculated according to the weights. The standardization process of passband evaluation values is as follows:

\[ K_{in} = 1 + \frac{f_{in} - f_{i0}}{f_{i0}} \]  

(23)

where \(K_{in}\) represents the standardized value of the \(i\)th passband evaluation value in the spectrogram under \(n\) MPa axial tension, \(f_{in}\) and \(f_{i0}\) represent the \(i\)th passband evaluation values in the spectrogram under 0 MPa and \(n\) MPa axial tension, respectively.
### TABLE 2  Multilevel evaluation indicator for spectrum characteristic evaluation

| First-level indicators | Second-level indicators | Third-level indicators |
|------------------------|-------------------------|------------------------|
| Spectrum characteristics $K_n$ | First passband characteristics $K_{1n}$ | Lower frequency $K_{1in}$ |
|                         |                         | Bandwidth $K_{1Wn}$ |
|                         |                         | Peak value $K_{1Pn}$ |
|                         |                         | Peak-corresponding frequency $K_{1fPn}$ |
|                         |                         | Energy $K_{1En}$ |
| ...                    | ...                    | ...                    |
| $l$th passband characteristics $K_{ln}$ | $l$th passband characteristics $K_{ln}$ | Lower frequency $K_{ln}$ |
|                         |                         | Bandwidth $K_{ln}$ |
|                         |                         | Peak value $K_{lpn}$ |
|                         |                         | Peak-corresponding frequency $K_{lfPn}$ |
|                         |                         | Energy $K_{lEn}$ |

### TABLE 3  Standardized data of passband and spectrum evaluation indicators

| Evaluation indicator | Axial tensile stress, MPa |
|----------------------|---------------------------|
|                      | Weight | 0 | 17 | 33 | 50 | 67 | 84 | 100 | 117 | 134 | 150 | 167 |
| Third level          |        |   |    |    |    |    |    |    |    |    |    |    |
| 1st passband        |        |   |    |    |    |    |    |    |    |    |    |    |
| $K_{1In}$            | 0.200  | 1.000 | 0.996 | 1.385 | 1.354 | 1.150 | 1.192 | 1.181 | 1.172 | 1.150 | 1.158 | 1.088 |
| $K_{1Wn}$            | 0.200  | 1.000 | 0.948 | 1.077 | 0.119 | 1.014 | 1.050 | 1.067 | 1.063 | 1.050 | 1.055 | 1.046 |
| $K_{1Pn}$            | 0.200  | 1.000 | 0.925 | 0.913 | 0.906 | 0.765 | 0.550 | 0.655 | 0.570 | 0.558 | 0.499 | 0.539 |
| $K_{1fPn}$           | 0.200  | 1.000 | 0.902 | 0.942 | 0.952 | 0.932 | 0.922 | 0.825 | 0.826 | 0.873 | 0.523 | 0.216 |
| $K_{1En}$            | 0.200  | 1.000 | 0.594 | 0.544 | 0.513 | 0.468 | 0.491 | 0.508 | 0.503 | 0.468 | 0.436 | 0.404 |
| 2nd passband        |        |   |    |    |    |    |    |    |    |    |    |    |
| $K_{2In}$            | 0.200  | 1.000 | 1.090 | 1.112 | 1.090 | 1.097 | 1.094 | 1.071 | 0.960 | 0.940 | 0.962 | 0.962 |
| $K_{2Wn}$            | 0.200  | 1.000 | 1.036 | 1.050 | 1.031 | 1.243 | 1.033 | 1.148 | 0.999 | 0.928 | 0.999 | 1.221 |
| $K_{2Pn}$            | 0.200  | 1.000 | 0.859 | 0.295 | 0.234 | 0.591 | 0.531 | 0.427 | 0.345 | 0.124 | 0.313 | 0.277 |
| $K_{2fPn}$           | 0.200  | 1.000 | 0.925 | 0.908 | 0.803 | 0.959 | 0.891 | 0.898 | 0.891 | 0.888 | 0.884 | 0.881 |
| $K_{2En}$            | 0.200  | 1.000 | 1.669 | 1.895 | 2.093 | 2.358 | 2.228 | 2.363 | 2.360 | 2.296 | 2.272 | 2.338 |
| 3rd passband        |        |   |    |    |    |    |    |    |    |    |    |    |
| $K_{3In}$            | 0.200  | 1.000 | 1.103 | 1.105 | 1.073 | 1.044 | 1.130 | 1.067 | 1.072 | 1.058 | 1.063 | 0.958 |
| $K_{3Wn}$            | 0.200  | 1.000 | 2.194 | 2.483 | 2.425 | 2.122 | 2.580 | 2.330 | 2.284 | 2.265 | 2.342 | 1.871 |
| $K_{3Pn}$            | 0.200  | 1.000 | 0.650 | 0.122 | 0.226 | 0.817 | 0.939 | 0.844 | 0.949 | 0.942 | 0.808 | 0.802 |
| $K_{3fPn}$           | 0.200  | 1.000 | 0.942 | 0.932 | 0.882 | 0.873 | 0.882 | 0.954 | 0.916 | 0.906 | 0.902 | 0.874 |
| $K_{3En}$            | 0.200  | 1.000 | 3.962 | 4.695 | 3.379 | 2.362 | 2.227 | 1.932 | 2.089 | 1.834 | 1.622 | 1.348 |

Second level

|                  |                  |                  |                  |
|------------------|------------------|------------------|------------------|
| 1st passband     |                  |                  |                  |
| $K_{1In}$        | 0.596            | 1.000            | 0.879            |
|                  | 0.890            | 0.990            | 0.821            |
|                  | 0.881            | 0.863            | 0.865            |
|                  | 0.847            | 0.841            | 0.764            |
|                  | 0.701            |                  |                  |
| 2nd passband     |                  |                  |                  |
| $K_{2In}$        | 0.272            | 1.000            | 1.134            |
|                  | 1.109            | 1.128            | 1.315            |
|                  | 1.220            | 1.260            | 1.200            |
|                  | 1.138            | 1.171            | 1.225            |
| 3rd passband     |                  |                  |                  |
| $K_{3In}$        | 0.132            | 1.000            | 1.949            |
|                  | 2.144            | 1.771            | 1.514            |
|                  | 1.627            | 1.484            | 1.520            |
|                  | 1.452            | 1.405            | 1.203            |
Table 2 shows the multilevel evaluation indicator for spectrum characteristic evaluation.

### 4.1.5 Evaluation process

The evaluation process of multilevel method based on improved radar chart to evaluate acoustic frequency spectrum includes the following steps: Firstly, acquire the time domain of acoustic signal in drill string from the ground receiving device and obtain the acoustic spectrum by fast Fourier transform. Secondly, determine the noise amplitude boundaries in the spectrum and the frequency bands are divided into passbands if its amplitudes are larger than the boundaries. The evaluation indicator data in each passband are extracted and standardized. Thirdly, draw the evaluation indicator of passband improved radar chart and calculate the evaluation function value. Fourthly, evaluate the passband characteristics according to the value of the passband evaluation function. The spectrum evaluation indicator data are extracted and standardized. Finally,
draw the improved radar chart and calculate the evaluation function value of spectrum. Evaluate the spectrum characteristics according to the value of spectrum evaluation function.

### 4.2 Evaluation results

Standardized data of passband evaluation indicators (third-level indicators) are shown in Table 3. Based on the data, the multilevel eigenvectors, evaluation vectors, and values of multilevel evaluation function are calculated by using the method of improved radar chart method. The third-level evaluation process is to calculate the evaluation function value of each passband by the evaluation indicators, and the corresponding value is taken as the evaluation indicator of the passband. Figure 9A shows the improved radar chart of six third-level evaluation indicators in first passband under 0 MPa and 167 MPa axial tensile forces. The second-level evaluation process is to calculate the evaluation function value of spectrum by the evaluation indicators, and the corresponding value is taken as the evaluation indicator of the spectrum. Figure 9B shows the improved radar chart of three second-level evaluation indicators in spectrum under 0 MPa and 167 MPa axial tensile forces. Table 4 shows the comprehensive evaluation values calculated by using the method of improved radar chart.

The following conclusions can be concluded from the evaluation results: (a) Axial tensile force has remarkable effect on the passband characteristics and spectrum characteristics of acoustic wave in drill string, and the influential level is distinct to different passbands. (b) With the increase of the axial tensile force, the changes of evaluation indicators of each passband are basically balanced. The 1st passband characteristics decrease obviously at the initial increase stage of the force and then decrease in the later increase stage. The 2nd passband characteristics increase obviously at the initial increase stage of the force and remain stable at the later increase stage, and the 3rd passband characteristics decrease sharply after a large increase at the initial stage and then remain stable. (c) With the increase of the force, the changes of spectrum characteristic evaluation indicators are basically balanced.

The stability of spectrum characteristics determines the transmission quality of acoustic signals in drill string. Therefore, in order to use the evaluation results to reduce the adverse effects of axial tensile force on acoustic signals in drill string during field application, the spectrum fluctuation coefficient is introduced. The spectrum fluctuation coefficient, \( B \), is defined as:

\[
B = \frac{K_n - K_0}{K_0} \times 100\%
\]

Table 5 Classification of acoustic frequency spectrum characteristics

| Spectrum grade | \( B \)          |
|---------------|------------------|
| Excellent     | \([4\%, +\infty)\) |
| Good          | \([2\%, 4\%)\)    |
| Mediate       | \([0, 2\%]\)      |
| Qualified     | \([-2\%, 0]\)     |
| Unqualified   | \([-4\%, -2\%]\)  |
| Bad           | \((-\infty, -4\%)\) |

**FIGURE 10** Relationship between spectrum fluctuation coefficient (\( B \)) and axial tensile stress

where \( K_0 \) and \( K_n \) represent the spectrum evaluation values under 0 MPa and \( n \) MPa axial tensile forces, respectively.
The spectrum characteristics under different axial tensile forces are classified according to the value of the spectrum fluctuation coefficient, as shown in Table 5. In field application, the classification results can guide the selection of carrier frequency and relay installation location.

Figure 10 shows the relationship between B and axial tensile force in drill string. The results show that B increases significantly for axial tensile force in the range of 0-33 MPa and then decreases in the later increase stage of the force, and the strongest point occurs when the stress is 33 MPa. The acoustic frequency spectrum is excellent in the range of 17-134 MPa for axial tensile force in drill string. However, when the axial tensile stress exceeds 134 MPa, the B decreases significantly, and when the axial tensile force exceeds 152 MPa, the spectrum is bad. In this range of force, methods such as adjusting the carrier frequency and relay installation location are needed to improve the transmission quality of acoustic signals.

5 | CONCLUSIONS

1. The interference of spectral characteristics is the key problem that restricts the transmission distance and quality of acoustic signals in field conditions. Axial tensile force has significant effect on spectrum characteristics.
2. The spectrum characteristics change with axial force. These changes manifest in the position, width, and attenuation of different passbands, and the extent of changes is distinct to different passbands.
3. The evaluation values of different passbands in the spectrum are selected as the evaluation indicators of spectrum characteristics. Both the evaluation indicators of each passband and the spectrum evaluation indicators are change with increasing axial tensile force.
4. The acoustic frequency spectrum is excellent in the range of 17-134 MPa for axial tensile force in drill string. When the stress exceeds 152 MPa, methods such as adjusting the carrier frequency and relay installation location are needed to improve the transmission quality of acoustic signals.

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