Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 14, No. 3, 2025

Structural Design and Analysis of Hydraulic Sandblasting Perforation Device

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Abstract: The coalbed methane reservoirs in China are mostly low-permeability reservoirs, which face many difficulties in mining, such as complex fractures, susceptibility to sand blockage, and low support rate. This article designs a new type of hydraulic sandblasting perforation device that integrates hydraulic sandblasting and perforation technology. It adopts a modular structure and includes guiding, adjusting, fixing, perforation, and stabilizing mechanisms. It is suitable for a well diameter of 139.7mm, a maximum outer diameter of 110mm, an inner diameter of 45mm, a total length of 450mm, a nozzle outlet diameter of 6mm, and a pressure bearing capacity of 90MPa. The fixed mechanism uses threaded rods and other components to achieve stable fixation, and the sandblasting perforator of the perforation system consists of a gun body, a protective cover, and a nozzle. According to static analysis, the maximum deformation value of the perforator is 0.015602mm, and the maximum stress is 235.31MPa, which is less than the allowable stress of 715MPa for the material, and the strength meets the requirements. Modal characteristic analysis shows that its first six natural frequencies are all above 3377Hz, much higher than the normal operating frequency of 100Hz, and it will not resonate during operation. This device can ensure the accuracy of sandblasting perforation, reduce the risk of accidents, and provide technical support for efficient exploitation of coalbed methane.

Keywords: Nozzle; Fracturing; Hydraulic sandblasting perforation device; Static analysis; Modal analysis.

1. Introduction

The coalbed methane reservoirs in China are mostly low-permeability reservoirs, and most wells have little production without fracturing. Therefore, hydraulic fracturing technology is one of the main production increasing technologies for coalbed methane development in China[1-3]. Hydraulic jet fracturing technology is a new type of stimulation and transformation technology that integrates perforation, fracturing, and isolation. It is suitable for the stimulation and transformation of vertical and horizontal wells in low-permeability reservoirs and is an effective method for fracturing and increasing production in low-permeability reservoirs. Due to the low elastic modulus of coal and rock, the soft formation, and the development of natural cleavage fractures, complex fracture propagation patterns are easily formed during coal seam hydraulic fracturing. Complex fractures develop in a network shape, with limited opening of individual fractures, easy sand blockage, and difficulty in improving sand ratio. The ultimate effective support rate of fractures is low, and the difficulty of extending fracture length is high [4-5].

With the huge demand for energy in the development of the national economy and the increasingly depleted energy crisis, energy exploration technology is forced to constantly innovate. It is necessary to increase and target the development of low-pressure, low-permeability, and low-permeability "three low" oil reservoirs and unconventional oil and gas resources such as coalbed methane and shale gas. Especially as oil and gas fields enter the middle and later stages, the utilization of reserves becomes increasingly difficult. In order to achieve stable and high yields, the focus of development has shifted to the previously overlooked thin layers of differential layers[6]. In order to develop these complex reservoirs quickly and efficiently, the concept of refinement is not only proposed in management, but also requires improvements in process technology [7-9].

This article designs a new type of hydraulic sandblasting perforation device, which is a device used for coalbed methane or coal seam water injection mining. It combines hydraulic sandblasting and perforation technologies to complete sandblasting and perforation operations of coal and rock layers in one device. It mainly includes two parts: hydraulic sandblasting system and perforation system. The hydraulic sandblasting system uses high-pressure water jet to wash the coal and rock layers to achieve the effect of fragmentation and dissolution, thereby improving the permeability of coalbed methane or coal seam water injection. The perforation system uses bullet guns or other forms of perforation tools to form holes in the washed coal and rock layers to facilitate the extraction or injection of coalbed methane or water [10-12].

In the process of mining coal seams, especially during sandblasting and perforation operations, it is usually necessary for workers to conduct simulation calculations in advance to determine the specific location of sandblasting and perforation required for the coal seam. However, in existing technologies, there is usually no positioning function for the device, which may cause the position of the sandblasting and perforation to shift due to its instability when using the device for sandblasting and perforation operations, thereby affecting the accuracy of sandblasting and perforation of the coal seam. In severe cases, it may even lead to coal seam collapse, posing a great safety hazard to the lives of workers.

2. Structural Design and Working Principle of a New Hydraulic Sandblasting Perforation Device

2.1. Overall structural design

Based on the principle of underground erosion and combined with the practical application requirements of the device, the scheme improvement of the hydraulic sandblasting perforation device has been completed, and a new type of fixable hydraulic sandblasting perforation device is proposed as shown in Figure 1. Then, modular design is adopted for the structure of the device, including five parts: guiding mechanism, adjusting mechanism, fixing mechanism, perforation mechanism, and stabilizing mechanism.

Figure 1. Overall structure of a new hydraulic sandblasting perforation device

2.2. Working principle

According to Figure 1, the working principle of the hydraulic sandblasting perforation device can be observed. When the guide head is started and placed inside the coal seam, the device can be guided to the designated position under the starting action of the guide head. Then, by starting the forward and reverse motor 2, the threaded rod 2 can be driven to rotate. Under the cooperating restriction of the guide rod 2, the adjustment cylinder 2 can be driven to slide inside or outside the adjustment cylinder 1. With the movement of the adjustment cylinder 2, the position of the electronic locator and guide head can be driven to move, thereby achieving fine adjustment of the position of the device after placement. After the adjustment is completed, when it is necessary to fix the device, people only need to start the forward and reverse motor 1. With the start of the forward and reverse motor 1, Drive the rotation of threaded rod one, and with the rotation of threaded rod one, And under the restriction of the guiding rod 1, it can drive the threaded block to move. With the movement of the threaded block, it can drive the movement of the fixed seat. With the movement of the fixed seat, it can drive the rotation of the driving rod. Through the rotation of the driving rod, under the support of the connecting column 2 and the connection of the connecting column 1, it can drive the limit claw to expand until it is inserted into the coal seam, thereby achieving the positioning and fixation of the device after placement. This effectively avoids the displacement of the sandblasting perforation position caused by its instability, further ensures the accuracy of sandblasting perforation of the coal seam, and avoids the problem of great safety hazards to the lives of workers caused by coal seam collapse in severe cases.

2.3. Determination of main design parameters

Based on the optimization results of nozzle structure parameters and production materials mentioned earlier, and taking into account the actual site conditions, a hydraulic jet fracturing downhole tool suitable for 51/2"casing was finally calculated. Combined with reference materials, preliminary design parameters for a new type of hydraulic sandblasting perforation wereproposed, as shown in Table 1.

Table 1. Main technical parameters of the new hydraulic sandblasting perforation device

Parameter name	numerical value
Applicable well diameter	139.7mm
Maximum outer diameter of the tool	110mm
inside diameter	45mm
Total length of tool	450mm
Diameter of nozzle outlet	6mm
pressure-bearing	90MPa

3. Fixed System Design

The fixed mechanism is the core component for achieving accurate positioning and stable fixation of the device in coal and rock layers. It consists of threaded rod 1, threaded block, fixed seat, driving rod, connecting column 1, limiting claw, and connecting column 2, as shown in Figure 2. When the threaded rod rotates, according to the principle of threaded transmission, the threaded block connected to it will move along the axial direction of the threaded rod. The outer surface of the threaded block is fixedly connected to a set of fixed seats, and as the threaded block moves, the fixed seats also move accordingly. The inner wall of each fixed seat is rotatably connected to a set of driving rods, and the inner wall of the driving rod is fixedly connected to a connecting column. When the fixed seat moves, the driving rod will rotate around the connecting column. The outer surface of connecting column one is rotatably connected to the limiting claw, and the inner wall of the limiting claw is fixedly connected to connecting column two, which is rotatably connected to the inner wall of the positioning cylinder. Through this structural design, when the driving rod rotates, under the support of the connecting column 2, the limit claw can expand or contract around the connecting column 1, achieving the fixation and release of the device in the coal rock layer.

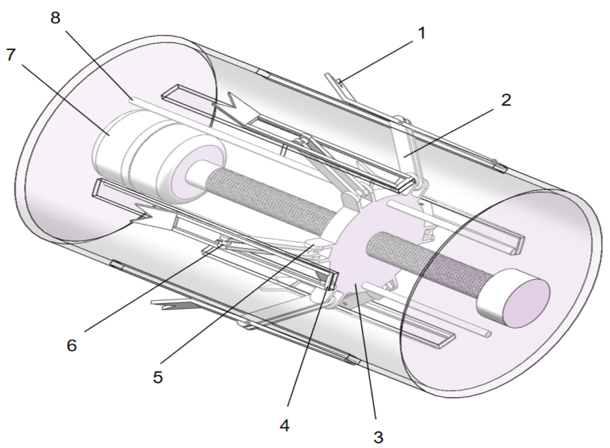


Figure 2. Schematic diagram of positioning cylinder structure

1-Limit claw; 2- Drive rod; 3-Thread block; 4-Connecting pillar two; 5- Fixed seat; 6-Connecting pillar one; 7-Forward and reverse motor one; 8-Guiding Rod One 一；

4. Perforation System Design

The perforation system is the core operational module of the entire hydraulic sandblasting perforation device, and its performance directly determines the efficiency and quality of coal and rock mining, as shown in Figure 3.

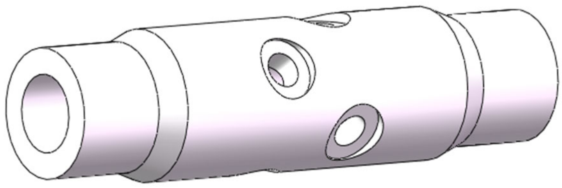


Figure 3. Schematic diagram of perforation system structure

4.1. Structure of Sandblasting Perforator

The spray gun assembly includes the gun body, protective cover, and nozzle, as shown in Figure 4, and is one of the key components in the entire fracturing pipe string. The high-pressure sand carrying fracturing fluid pumped into the ground will be converted into a high-speed jet through a small diameter nozzle, and then impact the inner wall of the casing to carry out perforation. The nozzle is installed in the conical hole of the body through the nozzle seat and sealed with the body using the conical surface; The external design of the spray gun body is equipped with a high-quality alloy protective layer, which aims to reduce the erosion effect of counterattack sand on the spray gun body during high-speed sand carrying fluid perforation.

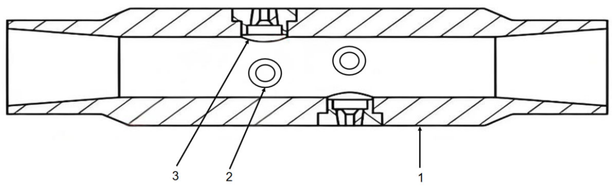


Figure 4. Schematic diagram of sandblasting perforator structure

1; Nozzle seat; 2- Nozzle; 3- Spray gun body

5. Static Analysis of Sandblasting Perforator

5.1. Simulation model establishment

The hydraulic sandblasting perforating device designed in this article is mainly subjected to the effects of high pressure zone, low pressure zone, and annular liquid pressure, as well as the pressure of the lower drilling tool during the working process. Therefore, its model was appropriately simplified during static finite element analysis, as shown in Figure 5.

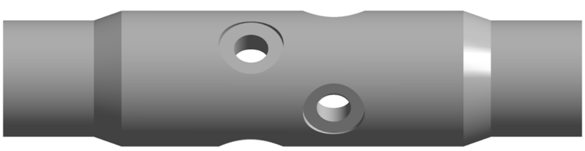


Figure 5. Finite Element Model of Hydraulic Sandblasting Perforator

5.2. Grid division and boundary condition setting

The hydraulic sandblasting perforating device was meshed with a mesh size of 5mm and a tetrahedral mesh type. The number of mesh nodes after partitioning was 69959, and the number of mesh elements was 40398. The mesh partitioning results are shown in Figure 6. Based on the actual force situation during the operation of the perforating device, a fixed constraint is added on both the upper and lower ends of the perforating device, and a normal pressure of 30MPa is applied on the outer cylindrical surface. The boundary conditions and loading conditions of finite element analysis are shown in Figures 4-7 (a) and (b):

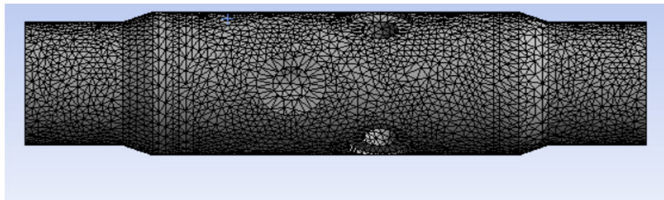
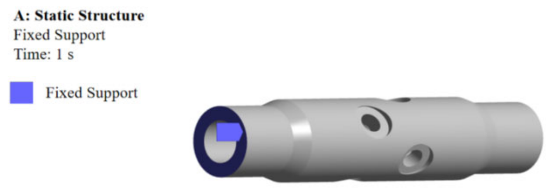
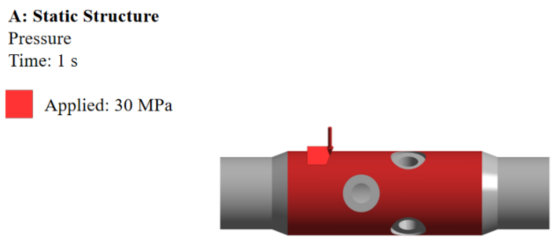


Figure 6. Grid division results



(a)Apply fixed constraints

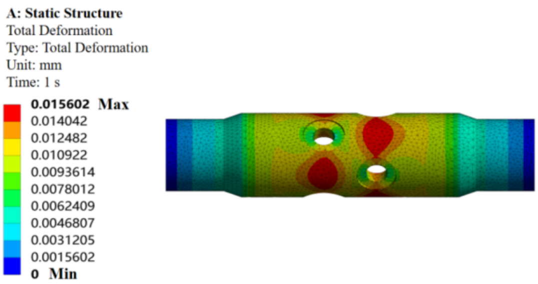


(b) Apply external pressure

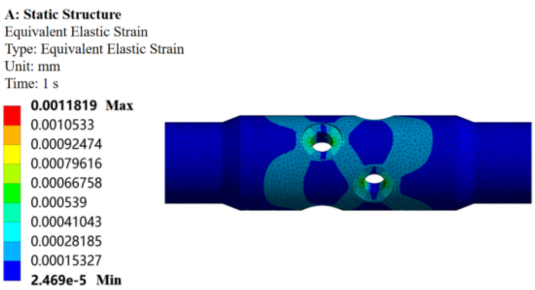
Figure 7. Application of boundaries and loads

5.3. Simulation result

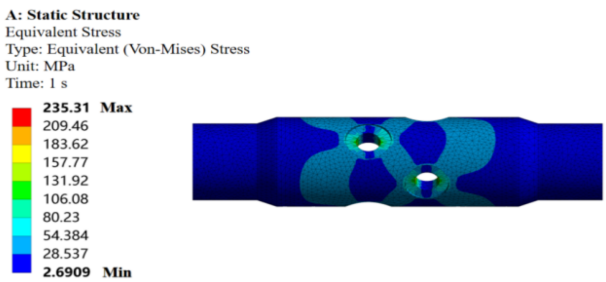
According to Figure 8, the maximum deformation value of the perforator in actual working conditions is relatively small, at 0.015602mm; The maximum stress experienced by the perforating device as a whole is 235.31MPa, and the maximum strain is 0.001819. The yield stress of 42CrMo material is 930Mpa, and assuming the safety factor of the hydraulic sandblasting perforator is 1.3, the allowable stress of the material is 715MPa. After finite element analysis, the maximum stress experienced by the perforating device as a whole is 235.31Mpa, which is less than the maximum allowable stress max of the material. Therefore, the strength of the perforating device can meet the requirements. According to the strength verification theory of the hydraulic perforator mentioned above, the allowable stress of the hydraulic perforator is 715MPa, so its strength is within the safe range when in use.



(a) Total deformation



(b) Equivalent strain



(c) Equivalent stress

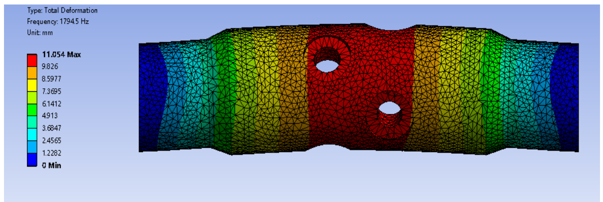
Figure 8. Static analysis of perforating device

6. Modal Characteristics Analysis of Sandblasting Perforators

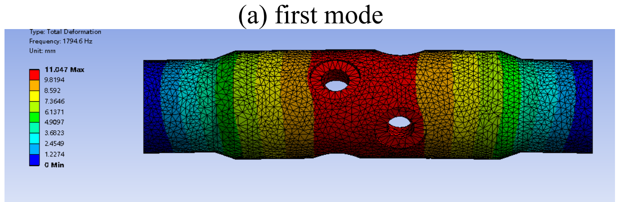
In engineering applications, modal analysis is widely used to identify the natural frequencies and vibration characteristics of components, which are collectively referred to as modes. To ensure the safety and reliability of the structure, the natural modal frequency of the component is usually compared and analyzed with its operating frequency to avoid resonance phenomena. When conducting modal analysis of perforating equipment, it is necessary to define the material performance parameters. In this paper, 42CrMo material is selected, with an elastic modulus E of 2.10 × 1011Pa, Poisson's ratio μ=0.28, and a density p of 7850kg/m3.

Table 2. Frequency table of the first six constrained modes of hydraulic injectors

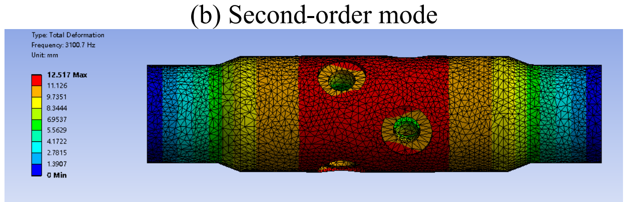
first mode	1794.5
Second-order mode	1794.6
Third order mode	3100.7
Fourth-order mode	4065.9
Fifth order mode	4066.0
Sixth order mode	5444.5



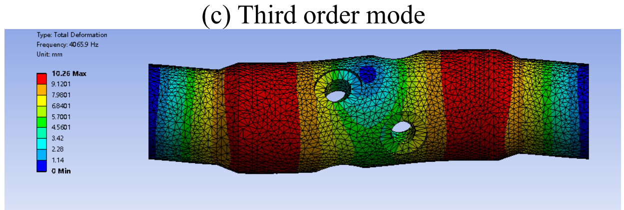
(a) first mode



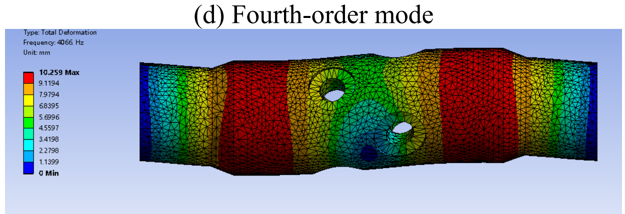
(b) Second-order mode



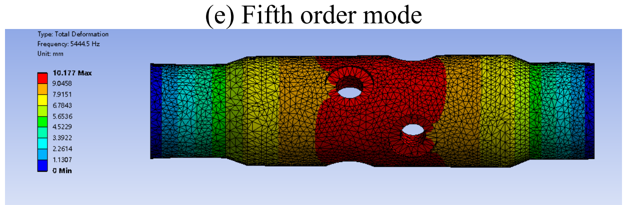
(c) Third order mode



(d) Fourth-order mode



(e) Fifth order mode



(f) Sixth order mode

Figure 9. Analysis cloud map of different modes of hydraulic sandblaster

Figure 9 shows the calculated deformation cloud map of the first six modes of the hydraulic injector under constrained conditions. From the results, it can be seen that the natural frequencies of each order of the hydraulic injector are all above 3377Hz. Considering that the normal operating frequency of the hydraulic injector is about 100Hz, much lower than these natural frequencies, the hydraulic injector designed in this article will not cause resonance phenomena during operation, which will effectively extend the service life of the tool and reduce the risk of underground accidents.

7. Conclusion

This article proposes a new type of hydraulic sandblasting perforation device to address the challenges of extracting low-permeability coalbed methane reservoirs in China. This device integrates hydraulic sandblasting and perforation technology, adopts a modular structure design, and the various mechanisms work together to achieve precise positioning, fixation, and efficient perforation operations of the device in coal seams. By determining reasonable design parameters, the applicability of the device is ensured. The fixed system utilizes threaded transmission and special structures to achieve stable fixation; The structural design of the sandblasting perforator in the perforation system is reasonable, effectively reducing the impact of erosion. The static analysis results indicate that the strength of the perforating device meets the standard, and the modal characteristic analysis shows that it will not resonate during operation, ensuring the safety and reliability of the device. The design of this device provides a new approach for coalbed methane mining, which is expected to solve the shortcomings of existing mining technologies, improve mining efficiency and production, promote the efficient development and utilization of coalbed methane resources, and have important application value and broad development prospects in the field of energy exploration and development.

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