STRUCTURAL ANALYSIS ON IMPACT-MECHANICAL PROPERTIES OF ULTRA-HIGH HYDRAULIC SUPPORT

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Abstract

With the increase of the mining height, the operational condition of the hydraulic support is getting worse. Since the column and the balance jack are both regarded as rigid structural parts or springs with constant stiffness, this simplification cannot reflect the characteristics of each stage of the working process. To improve the analysis accuracy, a rigidity-variable impact dynamic simulation platform for hydraulic support with ultra-large mining height based on rigidity-flexibility coupling is constructed in this study. Firstly, stress states of hinge joints of the support when parallel surface loads, raising surface loads and down surface loads act on the upper beam were simulated, and critical loads of different hinge joints were recognized. Secondly, dangerous impact positions of support corresponding to different hinge joints were found. Finally, the overall influences of impact loads on stress state of the hydraulic support were summarized. Results show that under 6000 kN impact load, the maximum force variation coefficient at the hinge point of the shield beam of the support roof is 10.5, and it's the most dangerous hinged position. This study has certain guiding significance for the optimization of the support structure.

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Key Words: Hydraulic Support, Mechanical Properties, Impact Load, Support Stability

1. INTRODUCTION

A hydraulic support is the core of underground support and it is the key equipment to maintain safety operation of coal face. Recently, length of underground coal face increases gradually to improve the mining efficiency. The 350 m ultra-long coal face is a new development direction. Moreover, hydraulic support also develops to adapt to high and ultra-high mining height to realize effective mining of deep and thick coal bed [1, 2]. With the increase of length of coal face and height of hydraulic support, the underground face width and gob increase accordingly. Consequently, pressure step on underground roof is decreased and the pressure intensity is increased [3]. Meanwhile, abnormal settlement and collapse of positions above the upper beam and gob roof may cause greater and greater impacts onto the support. Therefore, bearing capacity of the support in deep and ultra-long coal face is the key that determines safe and reliable support.

In all working conditions of a hydraulic support, the impact load has the greatest influence on its mechanical performance. The impact load can break the original force balance of the support, causing the support to lose its stability. In some cases, it will cause sloshing, and in the worst case, the deformation or falling will even happen to cause a collapse of the support face, which leads to a major mine accident. Therefore, an in-depth analysis of the impact load on the support performance is essential. And finding the hinge points which are sensitive to

the force response under the impact load can provide a basis for optimizing the strength of the support structure and improving its support stability.

2. STATE OF THE ART

Many studies concerning relationship between bearing capacities of underground support and roof and floor as well as the influences of impact loads on support bearing have been proposed. Based on many deep studies on the coupling relationship between support and surrounding rocks, Wang et al. [4] summarized the relationship between support and surrounding rocks into strength coupling, stiffness coupling and stability coupling. He proposed some key technologies to control surrounding rocks in high coal faces, such as stability coupling and stiffness coupling control between support and surrounding rocks as well as wall caving control. Verma et al. [5-7] concluded the interaction between support and surrounding rocks by constructing and analysing a two-dimensional finite element model of long-wall coal face. Besides, they evaluated the coal face through the hydraulic supports with different bearing capacities. On the basis of analysing stress on a support with high mining height when point loads act on the upper beam, Wan et al. [8] improved stiffness of the model and constructed an impact dynamic simulation platform of support based on variable stiffness of stand column to analyse stress response of different hinge joints of an ultra-high mining height support when point loads impact onto the shield beam. Zhao et al. [9] proposed technology of hydraulic support constant load subsection adjustment; Average cutting time of shearer is shortened by 21.7 % by this technology, which effectively weakens coal wall and meets requirements of subsection mining for thick coal seam. Wang et al. [10-13] analysed stress, stability and electro-hydraulic control system of hydraulic support pillar, effectively reducing the failure rate of hydraulic support and increasing its stability. Cheng et al. [14] analysed influence of pitch angle coal seam and mining advancing speed on hydraulic support resistance, put forward specific measures to reasonably improve tunnelling speed and control mining height, which are beneficial to direct hydraulic stability. Meng et al. [15] established a mathematical model for detecting and controlling pose and orientation through electromechanical fluid simulation, and verified model with different poses to obtain a pose controller, which provides guidance for automation and unmanned underground mining. Witek and Prusek [16] carried out numerical simulation and analysis of laboratory tests on shield support and compared the solutions. The conclusion was drawn that the form of foundation support had influence on the stress distribution of shield. When the support was carried out over the whole length, the front load was reduced by about 45 %, which can provide guidance for shield support under specific geological conditions. Oblak et al. [17, 18] optimized some parameter values of leading four-bar mechanism to ensure that hydraulic support meets daily requirements on the premise of minimum lateral displacement based on the numerical simulation method. Zhang et al. [19] conducted finite element analysis of hydraulic cylinder stiffness based on fluid mechanics and fluid-solid coupling foundation, which has certain reference value for hydraulic cylinder stiffness analysis and hydraulic system design.

In previous studies, the balance jack was regarded as a rigid structural part, or as a spring of equal stiffness, and it did not show the two working characteristics (push and pull) of the balance jack. The research method of equivalent replacement of balanced jacks with stiffness springs, and based on this, a comprehensive summary of the force state of the bracket under surface load and point load impact was designed to find dangerous impact conditions and positions. According to above theories and studies, impact analysis method onto the support was further improved and stresses of support under surface loads and point loads were summarized, aiming to recognize the dangerous impact condition and positions.

The remainder of this study is organized as follows. Section 3 introduces the physic mode, numerical method, and force analysis of support under different surface and point impact loads. Section 4 analyses the result with different parameter setting and discusses the force variation of different parts in details. Section 5 summarizes the conclusions.

3. METHODOLOGY

3.1 Construction of the simulation platform

A ZY21000/38/82D impact dynamics simulation platform (height of the support model in the platform is the maximum working height) was constructed by combining three assisted modelling simulation analysis platforms of Pro/E, HyperMesh and ADAMS. The construction process is shown in Fig. 1. Firstly, the original three-dimensional model is constructed by using Pro. E. Secondly, main structural components of the support are processed to be flexible by HyperMesh (considering slight deformation of structural components after impacts of the support and its influence to stress of the support, all structural components except the base are flexible). Finally, an impact dynamics simulation platform of the support based on stiffness-flexibility coupling (centre pillar and the balance jack in the model are replaced by the damping system of a spring to realize compression boosting characteristics of an oil cylinder) is constructed by using ADAMS.

Figure 1: Construction process of the platform.

3.2 Stiffness processing of the simulation platform

During underground service of the hydraulic support, the column and balance jack have their own bearing capacities. When the support is lifted to a certain height and then the roof falls slowly, pressure over the roof increases gradually. The bearing mode of column has a specific process. Firstly, it shows initial bearing force (this state can be realized by preload) under low external loads. With the increase of external loads, upper cavities on columns begin to be compressed (at this moment, the column stiffness is equal to the upper cavity stiffness K_U , the column stiffness is equal to the lower cavity stiffness K_L). With the continuous increase of external load, the upper and lower cavities of column are compressed simultaneously (at this moment, the column stiffness is equal to the series stiffness of upper and lower cavities K_S). This process is shown in Fig. 2. In addition, the balance jack is “tensile” when the emulsified liquid in cavity is compressed (in this case, stiffness of the balance jack is equal to stiffness of column with cavity K_T); otherwise, it is “compressed” when no emulsified liquid in cavity is compressed (in this case, stiffness of the balance jack is equal to the cavity-free column stiffness K_C). The bearing process is shown in Fig. 2.

Figure 2: Compression process of the hydraulic cylinder.

According to working state of the above hydraulic cylinder, these series of stiffness can be calculated according to the equivalent stiffness formula of hydraulic cylinder as Eq. (1) and specific structural size (Fig. 3 and Table I) of hydraulic cylinder when the support is at the highest state as follows.

$$K = \frac{A\beta}{L} \quad (1)$$

where K is the equivalent stiffness coefficient (N/m). A is the equivalent area when hydraulic cylinder transfers pressure of liquid (m^2). β is volume elasticity modulus of the hydraulic fluid. The oil-in-water emulsion is 1.95×10^3 MPa. L is length of effective liquid column in the hydraulic cylinder (m).

Figure 3: Structures of column and balance jack.

Table I: Specific sizes of hydraulic cylinder (mm).

L_1	L_2	d_1	d_2	L_3	L_4	d_3	d_4
2113	2197	530	380	755	100	320	230

Therefore, the equivalent stiffness of the upper cylinder is expressed as follows.

$$K_U = \frac{\pi d_2^2 \beta}{4L_2} = 1 \times 10^8 \text{ N/m} \quad (2)$$

The equivalent stiffness of the lower cylinder can be expressed as follows.

$$K_L = \frac{\pi d_1^2 \beta}{4L_1} = 2.04 \times 10^8 \text{ N/m} \quad (3)$$

The series stiffness between the upper and lower cylinder is expressed as follows.

$$K_S = \frac{K_U K_L}{K_U + K_L} = 6.71 \times 10^7 \text{ N/m} \quad (4)$$

Stiffness when the balance jack is tensile is expressed as follows.

$$K_T = \frac{\pi(d_3^2 - d_4^2)\beta}{4L_3} = 1 \times 10^8 \text{ N/m} \quad (5)$$

Stiffness when the balance jack is compressed is expressed as follows.

$$K_c = \frac{\pi d_3^2 \beta}{4L_4} = 1.568 \times 10^9 \text{ N/m} \quad (6)$$

The above values of equivalent stiffness are input into the spring damping system of the platform to accomplish setting of stiffness.

Since the roof shape during underground service of hydraulic support is complicated and changing, the contact state between the upper beam and roof is complicated and changing. If the roof is relatively flat, the top surface of the upper beam and roof might have a large contact area, which is viewed as surface contact. If the roof is irregular, there's small contact area between top surface of the upper beam and small bumps, which is viewed as point contact.

Since the hydraulic support has a generally symmetric structure in this study, stress on hinge joints in the left side could be analysed firstly when the support faces to the coal wall. Hinge joints in the right side shall be considered in the final conclusions.

3.3 Stress analysis of the support under surface impact loads

The support has “down” or “raising” (or “aerogun”) bearing mode, which is determined by the slope and breaking points of roof [20, 21]. Several bearing states of support are shown in Fig. 4. According to these bearing states, the simulation platforms under “parallel surface impact”, “raising surface impact” and “down surface impact” are constructed (in Fig. 5, loading under different conditions are accomplished by setting the upper beam-roof contact as well as revolute pair and slippage pair on roof). Later, stress states of the support are discussed.

Figure 4: Bearing mode of the support.

Figure 5: Simulation platform of surface impacts.

The maximum working resistance of the support is set 21000 kN. The actual working resistance of the support in underground space generally ranges between the setting load and maximum working resistance. Here, the normal roof pressure during underground service of the support is determined 14000 kN. Meanwhile, 6 groups step loads from 1000 kN to 6000 kN are chosen as the impact loads under three conditions. All loads are perpendicular to the roof centre of the model. Specific curves of different loads are shown in Fig. 6.

Figure 6: Roof pressure and impact loads.

4. RESULT ANALYSIS AND DISCUSSION

4.1 Stress of supports under surface impacts

Simulation is carried out based on above models. Stresses at different hinge joints of the support could be gained. For the convenient of contrast analysis, all results are processed according to Eq. (7) as follows.

$$Z = \frac{F_{max} - F_a}{F_a} \quad (7)$$

where, Z is the variation coefficient of stress at different hinge joints. F_{max} is the maximum stress at different hinge joints after surface impacts to the support. F_a is the stability value of stress at different hinge joints when the support bears 14000 kN pressure from the support roof.

Variation coefficients of stresses on columns, hinge joint between the upper beam and shield beam (hereinafter referred as the “upper-shield beam hinge joint”), hinge joint of the front linkage, and hinge joint of the rear linkage are shown in Figs. 7 to 10.

Figure 7: Variation coefficient of stress on columns.

Figure 8: Variation coefficient of stress on upper-shield beam hinge joint.

It can be seen from Fig. 7 that variation coefficients of stress on columns under three surface impacts all achieve a linear growth trend with the increase of impact loads. Moreover,

the variation coefficient of stress under parallel surface impact is increased to the maximum. In other words, stress of column is positively related with impact loads and it is mostly sensitive to impact loads under parallel surface impact.

Fig. 8 shows that variation coefficients of stress on upper-shield beam hinge joint under three surface impacts all achieve a linear growth trend with the increase of impact loads. Moreover, the variation coefficient of stress under raising surface impact is increased mostly. This reveals that the stress of upper-shield beam hinge joint is positively related with impact loads and it is mostly sensitive to impact loads under raising surface impact.

Figure 9: Variation coefficient of stress on hinge joint of front linkage.

Figure 10: Variation coefficient of stress on hinge joint of rear linkage.

In Fig. 9, variation coefficients of stress on hinge joint of front linkage under three surface impacts all achieve a linear growth trend with the increase of impact loads. Moreover, the variation coefficient of stress under raising surface impact is increased mostly. This reveals that the stress of hinge joint of front linkage is positively related with impact loads and it is mostly sensitive to impact loads under raising surface impact.

It can be seen from Fig. 10 that variation coefficients of stress on hinge joint of rear linkage under three surface impacts all achieve a linear growth trend with the increase of impact loads. Moreover, the variation coefficient of stress under raising surface impact is increased mostly. This reveals that the stress of hinge joint of rear linkage is positively related with impact loads and it is mostly sensitive to impact loads under raising surface impact.

4.2 Stress analysis of the support under point impact

Point impact is different from surface impact and it might act at random positions of the support. Since rock collapse in gob from underground roof might generate impact loads to the shield beam, point impact is also divided into three working conditions: “point impact on the upper beam”, “point impact on shield beam” and “point impact on upper beam and shield beam simultaneously”. Loading schemes of point impact are shown in Figs. 11 to 13. The loading curves of positive external loads and point impact are shown in Fig. 14 (see Section 3.3). In this study, two positive loads (7000 kN) are chosen to act downward above the nest of upper beam perpendicular to the top surface of upper beam to simulate a roof pressure of 14000 kN. The impact load is set a 6000 kN step loads.

Figure 11: Impact loads act on the upper beam.

Figure 12: Impact loads act on shield beam.

Figure 13: Impact loads act on the upper beam and shield beam simultaneously.

Figure 14: Positive external loads and impact loads.

Stresses on different hinge joints are simulated. Later, results are processed according to the Eq. (7) in Section 4.1. Variation coefficients of stress at different hinge joints can be gained.

4.3 Variation coefficient of stress on column

Variation coefficient of stress on column increases under all three points impact conditions. Moreover, the variation coefficient of stress on column is increased mostly when point loads act on front end of upper beam and front end of shield beam. It can be seen from Fig. 15. This reflects that stress on column is increased when the impact loads act at any position of upper beam and shield beam. Moreover, impact loads at front ends of upper beam and shield beam are the most obvious.

Figure 15: Variation coefficient of stress when point loads impact on upper beam, shield beam and both simultaneously.

4.4 Variation coefficient of stress on upper-shield beam hinge joint

Based on Fig. 16, variation coefficient of stress at upper-shield beam hinge joints might increase and decrease when there's point impact on the support. Generally, variation coefficient of stress increases more when there's point impact on the front end (especially the left front position) of upper beam and front end (especially the right front position) of shield beam. This means that stress on upper-shield beam hinge joint might increase or decrease under point impacts on the support. However, the support shows the most response to impact loads on the front end (especially the left front position) of upper beam and front end (especially the right front position) of shield beam.

Figure 16: Variation coefficient of stress on upper-shield beam hinge joint when point loads impact on upper beam, shield beam and both simultaneously.

4.5 Variation coefficient of stress on front linkage

It can be seen from Fig. 17 that variation coefficient of stress at hinge joint of front linkage might increase and decrease when there's point impact on the support. Generally, variation coefficient of stress increases more when there's point impact on the front end (especially the right front position) of upper beam and front end (especially the right front position) of shield beam. This means that stress on hinge joint of front linkage might increase or decrease under point impacts on the support. However, the support shows the most response to impact loads on the front end (especially the right front position) of upper beam and front end (especially the right front position) of shield beam.

Figure 17: Variation coefficient of stress on hinge joint of front linkage when point loads impact on upper beam, shield beam and both simultaneously.

4.6 Variation coefficient of stress on rear linkage

It can be seen from Fig. 18 that variation coefficient of stress at hinge joint of rear linkage might increase and decrease when there's point impact on the support. Generally, variation coefficient of stress increases more when there's point impact on the front end (especially the

left front position) of upper beam and front end (especially the left front position) of shield beam. This means that stress on hinge joint of rear linkage might increase or decrease under point impacts on the support. However, the support shows the most response to impact loads on the front end (especially the left front position) of upper beam and front end (especially the left front position) of shield beam.

Figure 18: Variation coefficient of stress on hinge joint of rear linkage when point loads impact on upper beam, shield beam and both simultaneously.

4.7 Sensitive area of support to point impact

Based on above analysis, responses of hinge joints to point impacts at different positions of upper beam and shield beam could be concluded. According to response intensity, sensitive areas of hinge joint at point impact to the support can be obtained for further optimization of a hydraulic support (see Fig. 19).

Figure 19: Sensitive areas of hinge joints to impacts.

5. CONCLUSION

Analysis method for variable stiffness of hydraulic support multi-cylinder was proposed based on analysing working process of upright post and balance jack. Combined with specific structure of the cylinder, equivalent stiffness of support cylinder in different states was obtained by stiffness calculation formula. Conclusions are drawn as follows.

(1) Stress at different hinge joints of the support is positively related with surface impact loads under all three conditions. Stresses at the upper-shield beam hinge joint, hinge joint of

front linkage and hinge joint of rear linkage are the most sensitive to raising surface impact, while stress of column is the most sensitive to parallel surface impact. In general, raising surface impact influences stress of the support mostly.

(2) Stress at different hinge joints of the support under point impact might increase or decrease. Most point impacts may increase stresses at hinge joints of the support. For a column, the front end of the upper beam and front end of the shield beam are mostly sensitive to impact loads. The upper-shield beam hinge joint, hinge joint of the front linkage and hinge joint of the rear linkage are mostly sensitive to impact loads in the left and right front ends of upper beam and shield beams. Hence, impact loads on the front ends of upper beam and shield beam as well as on the left/right front ends influence stress state of the support mostly.

A dynamic load-bearing simulation model of hydraulic support with variable stiffness is established in this study, and stress responses of each support hinge point under surface load and point load impact are obtained through simulation. However, a hydraulic support contains many complex parts. In future work, influence of rib fall on stress of the support shall be considered to establish a more complex stress model of the support, and to perform researches on the influence of more external loads on the support.

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