Paper No. 231

ISMS 2016

Characteristics of acoustic wave velocity variation in the process of deformation and failure of loading coal

LI Xiangchun [a,b,*], NIE Baisheng [a,b], YANG Chunli [c], CUI Zhe [a,b], MAO Yanjun [a,b]

[a] School of Resource and Safety Engineering, China University of Mining & Technology(Beijing), Beijing, China, 100083
[b] State Key Lab of Coal Resources and Safe Mining, Beijing, China, 100083
[c] School of Mechanics and Civil Engineering, China University of Mining and Technology, Beijing, China, 100083

ABSTRACT
For studying characteristics of acoustic wave velocity change during the deformation and fracture of loaded coal, using self-made acoustic parameter test system the characteristics of acoustic wave velocity change in deformation and fracture of loaded coal, the mechanism of stress influencing acoustic wave velocity change, the relation between stress and longitudinal wave velocity and the impossibility of longitudinal wave velocity forecasting coal structure is studied. The research results show that during the deformation and fracture of loaded coal the longitudinal wave and shear wave velocity increases firstly. When the coal is damaged the longitudinal wave velocity decreases and the shear wave disappears. The stress-strain change of coal is similar to the stress-wave velocity change highly. Based on coal structure the formula of stress and longitudinal wave velocity is established and the longitudinal wave velocity can be predicted well under different stress by the formula of stress and longitudinal wave velocity. The mechanism of stress influencing acoustic wave velocity change is coal structure change mainly.
KEYWORDS: coal body; loading; stress; deformation and failure; wave velocity

1. INTRODUCTION

Coal and rock dynamic disaster is a sudden dynamic appearance caused by the dynamic evolutions of coal body deformation and rupture. As a geophysical method, acoustic detection technology (Liu and Cheng., 1999) has been used in the prediction of coal and rock dynamic disasters. Due to the complexity of coal and rock dynamic disasters, if we want to truly achieve accurate prediction and forecast, the further research on the transmission mechanism of acoustic wave in the coal body, the spatial distribution of the acoustic wave and the space-time distribution of the acoustic wave are needed to be done. Therefore, it is necessary to research on the characteristics of acoustic wave propagation in the whole process of deformation and failure.

At home and abroad, a lot of work has been done to study the relationship between stress and wave velocity. In the condition of hydrostatic pressure, the velocity law of metamorphic variation rocks was studied by Christensen (1965). The results show that the rock wave velocity changes with pressure and pore arrangement in rock mass are related to the fracture morphology. Freund (1992) try to research on the variation of the longitudinal and shear velocity of the arenaceous rocks under the multi-parameter condition of the presence of clay content, porosity and confining pressure. Under the pressure of loading conditions, the existence state and closure state of rock micro fissures and cracks were studied by King et al. (1995). It is concluded that there is a correlation between them and the velocity in the loading process and the shear velocity is related to the micro fracture and the crack closure which is perpendicular to the direction of propagation. Based on the analysis of the compaction effect of the 45 samples by Shi et al. (2004), the acoustic velocity of rock is related to the rock porosity, the pore fluid, the structure of the skeleton and the effective pressure on the rock. Based on case of the colliery No.3 of Huainan coalfield in Anhui Province, Peng et al. (2005) researched on the relations of acoustic velocity and mechanical characteristics of the lithofacies transition rock mass by the physical modeling study and numerical simulation technique. The results show that acoustic velocity increases with the stress increasing. In low stress conditions, the acoustic velocity increases obviously with the stress increasing and becomes steady with the stress increasing. The relationship between coal rock physics parameters and acoustic wave velocity was studied by (Meng and Zhang, 2006; Meng et al., 2008), which shows that the difference between the acoustic wave velocities of different lithology is relatively large, the acoustic wave velocities of rock are the main factors in addition to the composition and structure, mainly rock density and stress and groundwater factor. The granite, gneiss and marble and sandstone loading by Zheng et al. (2009), explore rock wave velocity with

*Corresponding author – email : chinalixc123@163.com

the response characteristics of changes. Experiment results show that the granite and gneiss during the linear elastic loading phase, velocity-stress rises linearly, velocity-stress is quadratic nonlinear change. The damage characteristics of salt rock under uniaxial loading are studied by using acoustic wave technique by Jiang et al. (2009). Along with the increase of the axial stress, the lateral wave velocity is smaller, and the wave velocity decreases rapidly after reaching the ultimate strength. Acoustic test to study the impact trend coal seam by Gong et al. (2012). The experiment was conducted under the condition of uniaxial stress loading path. The results show that with the increase of tress, the changes of longitudinal wave velocity of rock samples faster than the changes of longitudinal wave velocity of coal samples; in the elastic deformation stage of coal sample loading, the impact tendency of the coal rock is greatly increased, with the increase of stress, the deformation enters into the plastic stage, and the speed change area is gentle. It shows that there is a power exponent function relation between the stress change and the change of the wave velocity.

From these studies, it can be seen that the studies on the characteristics of acoustic wave change in the process of loading and failure of coal are less. Some studies are only preliminary studies. The change law and response mechanism of acoustic wave in different stage of coal deformation and failure need to be further analyzed. That the characteristics of acoustic wave variation in the process of coal loading and failure and analyses mechanism of stress influencing on the change of acoustic wave velocity were studied. The relationship between longitudinal wave velocity and stress is also discussed, and the possibility of predicting the structure of pore and fracture in coal body is discussed in order to provide theoretical basis for prediction of coal and rock dynamic disaster.

2. EXPERIMENT

2.1 Experiment System

The system includes coal sample clamping system, stress loading system, acoustic excitation system and wave receiving and acquisition system. The system structure of the system is shown in Fig.1. Coal sample holding system can be put into the standard sample of Φ25mm×50mm standard coal sample, through the interface to connect stress loading system, which is connected to an acoustic wave excitation system and acoustic wave receiving system through an end head with sound wave transducer. Force loading system for manual hydraulic loading system, which can achieve, two different loading and triaxial loading process, uniaxial loading and triaxial loading, axial pressure and confining pressure of different loading modes were achieved: constant pressure loading, step loading and cyclic loading, wave velocity variation under different loading modes and loading conditions were studied. At the two ends of the coal sample has two detachable ends, the first coal sample is put in the experiment, one end of the end is fixed, and the other end of the end head can be moved under the action of hydraulic pressure to achieve the loading of coal samples. Acoustic wave excitation system was developed by the State Key Laboratory of Southwest Petroleum University. For the sound wave pinger and acoustic probe (sound wave energy converter) its longitudinal wave frequency is 500 kHz and the shear wave frequency is 200 kHz. When system is connected to the digital oscilloscope, sound wave energy converter emitting end of the shear and longitudinal waves are in turn connected to the sound wave pinger of shear and longitudinal waves on the interface connecting lines, the digital oscilloscope external input terminals and EXT connection head of sound wave pinger are respectively connected with a moderate length of double shielded wire, and the two connecting head of the other sound wave energy converter are respectively connected to two CH1 and CH2 terminal on the digital oscilloscope. The acoustic wave receiving and acquisition system use the DSO7012B model of the dual channel oscilloscope, which can be used to measure the time difference between the longitudinal wave and the shear wave passing through the coal sample at the same time.

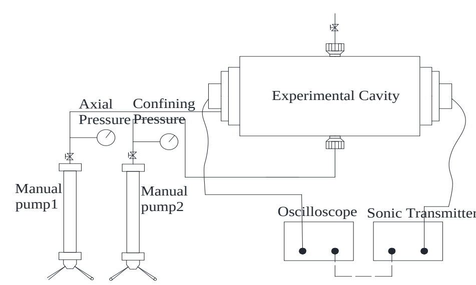


Figure 1: Schematic diagram of acoustic wave parameter test system in coal and rock

2.2 Coal Sample

The coal sampling of this experiment is come from Shanxi Guandi Coal Mine and Malan Mine2#, which is made to the standard of Φ25mm×50mm, coal sample section of flatness error is less than 0.02mm, the preparation of coal samples were vacuum drying (12 hours), and placed in dry bottles stored for a long time. Industrial analysis data of coal sample is shown in Table.1.

Table 1: Industrial analysis of the coal samples

coal mine	moisture content（%）	Air dry base volatile（%）	Dry basis ash（%）	Fixed carbon（%）
Malan 2#	0.48	24.55	5.69	69.29
Guandi	0.82	13.28	11.03	75.48

2.3 Experimental Programs

In this experiment, the variation of longitudinal and shear velocity of loading coal in uniaxial loading is studied. During the loading process, the test direction of wave velocity is the same as the direction of axial load of the axial load when the coal sample that the axial load of coal is loaded is destroyed. Limited by the design of the experimental instrument, the deformation of coal sample can only be measured in axial deformation.

2.4 Experimental Procedures

Firstly, coal sample is placed in a coal sample holding system, stress loading system, acoustic excitation system and the sound receiver acquisition system were connected, then the experiment starts, the acoustic velocity of coal samples was measured in the no pressure condition, and in accordance with the pre-set pressure of axial compression loading step by step, sample acoustic velocities of each stage on a loading pressure condition were measured, the experiment ends until the coal is destroyed.

3. EXPERIMENTAL RESULTS

3.1 Measure Principles

The usual method of measuring acoustic velocity is that measuring the ratio that sound wave transmission medium of unit length per unit time. The calculation formula is as follows.

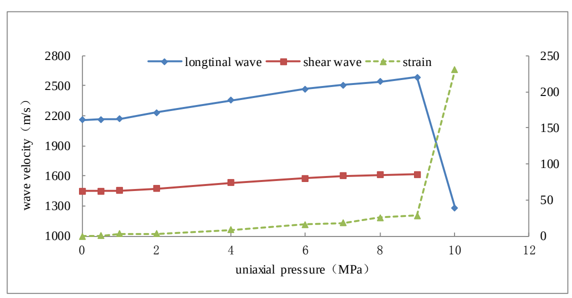
$$V = \frac{L}{T} \tag{1}$$

Where L the coal sample length, m; T the propagation time of acoustic wave in the medium, s; V the coal and rock mass acoustic wave velocity, m/s.

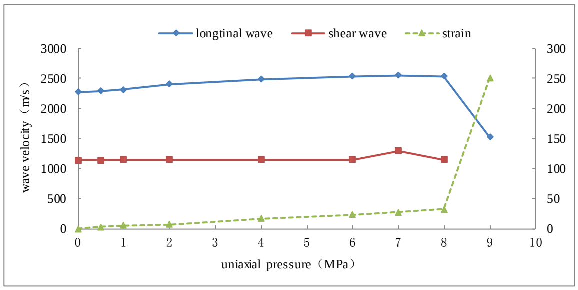
3.2 Experimental Results

The experiment selected three groups of coal samples, Guandi mine, Malan mine 2#, the change trend of the experimental results is similar, therefore, the typical of a group selected of experimental data is analyzed. Fig.2 shows that the experimental results of the damage process for the Malan mine 2# coal and Guandi coal. The experimental results show that the velocity of longitudinal wave velocity of coal and rock mass increases until the rupture velocity of coal body decreases, and the shear wave velocity increases firstly, but when the coal body breaks down, the shear wave disappears signally. This is mainly due to the coal and rock mass under loading, the deformation can be divided into two stages: (1) the elastic-plastic deformation stage, namely under stress, voids and fissures inside coal and rock tends to be closed; (2) deformation and failure stages, with the external load stress increasing, beyond the limits of coal and rock mass stress, coal body structure occurred deformation damage, pore fissure structure secondary development. The characteristics of the elastic and plastic deformation stage of the specimen and the change of the wave velocity in the deformation and failure stage. In the elastic plastic deformation stage, with the rapid closing of the pore crack, the acoustic wave velocity increases gradually, and the change of the longitudinal wave velocity is more obvious than that of the shear wave. In deformation and failure stages, after the uniaxial stress loading is beyond the limit of stress, and its internal structure began to damage, micro cracks and micro cracks begin develop to the coal rock breaked and fractured (Fig.3). In the coal and rock mass fragmentation fracture moment, its shape variable occurs suddenly Corresponding sample in loading process of stress-strain of the force velocity law also appeared mutation, in specimen loading moment of failure, acoustic velocity decreased suddenly. The shear wave velocity attenuation is much larger than the attenuation of the longitudinal wave velocity, so that the acoustic wave receiving probe is difficult to receive its attenuation signal.

In addition, Fig.2 shows samples stress-strain curves and stress-wave velocity curve have a high degree of consistency. It is also indicated that the acoustic wave velocity can be used as an indicator, which can reflect the stress state and the deformation of the internal structure in coal and rock mass, especially, the change of longitudinal wave velocity can be used as a good indicator that evaluates the stress state and the deformation of the internal structure in coal and rock mass.



Malan 2# coal



Guandi coal

Figure 2: Wave velocity changes with increasing pressure under uniaxial loading

Malan 2# coal Guandi coal

Figure 3: Fracture map of coal sample under uniaxial loading

4. THE RELATIONSHIP BETWEEN AND LONGITUDINAL WAVE VELOCITY

In a sense, the wave velocity of coal and rock mass mainly depends on the degree of porosity and fracture, namely porosity (Xu et al., 2015). Generally speaking, with the porosity increasing, the wave velocity decreases sharply. The experimental results show that the wave attenuation is very large, so it is difficult to receive the signal when the coal body breaks down. Therefore, it is more significant to study the longitudinal wave in the study of coal and rock deformation and rupture, it is necessary to analyze the relationship between the wave velocity and stress change.

Many scholars have done a lot of work to research on the relationship between wave velocity and stress. These relations include mainly two kinds of fitting formula and theoretical formula. For example, Wang and Xian (1988) for the rock under elastic stress, it is considered that the relationship between stress and elastic wave velocity can be expressed in a linear dependence coefficient. Nur (1997) considered that the stress and the wave velocity are in accordance with the two function relation. Huang (1991) established the relationship between wave velocity and stress by multiple regression analysis. Zhao and Wu (1999) based on linear elastic fracture mechanics and the assumption that the shape of the crack in the rock is ellipsoid, the relationship between wave velocity and stress is established. Gong et al. (2012) establish a power function relationship between force and velocity by fitting. Chen et al. (2010) believe that there is a transition point in the change of the velocity of rock during the loading and failure process. Below the transition point, the relationship between stress and wave velocity is in the form of power function. And above the transition point, the relationship between stress and wave velocity is in accordance with the two functions. One of the characteristics of these formulas is that the mathematical relation between stress and wave velocity is mainly considered, and the characteristic of wave equation can be known that the elastic wave velocity is related to the structure of the elastic body. They are related to the porosity of the rock, the degree of fracture development, or the degree of closure of the hole under a stress state (Din, 1997). Therefore, it is more scientific and reasonable to establish the relationship between the structure change of the hole and the change of the wave velocity through the stress action. Previous studies have showed that there is a mathematical relationship between the longitudinal wave velocity and the porosity (Luan and Hu, 1985).

$$\phi = be^{aV_p} \tag{2}$$

Where ϕ the porosity, %; a, b the constant; V_P the longitudinal wave velocity, km/s.

Before and after the destruction of coal, porosity changed greatly. It is difficult to use a unified formula to show the porosity change before and after the destruction of coal, so it is difficult to establish a uniform stress effect on the wave velocity change formula. Based on this, the main consideration is to establish the formula of the velocity change of the stress before the failure.

This is the relationship (Tao et al., 2010) between porosity and stress before failure:

$$\phi = 1 - \frac{(1-\phi_0)}{\exp(-K_y\sigma)} \tag{3}$$

Where ϕ the initial porosity, %; σ the stress, MPa; K_y the volumetric compression coefficient, MPa-1.

The formula (3) taken into the formula (2) can get the relationship between stress and longitudinal wave velocity:

$$V_p = \frac{1}{a}\ln\left(\frac{1-\dfrac{(1-\phi_0)}{\exp(-K_y\sigma)}}{b}\right) \tag{4}$$

According to the parameters measured in the laboratory, as Table.2 shown, a and b can be obtained by using the formula (4) to fit.

Table 2: a, b constant

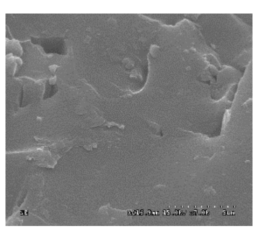
coal	ϕ_0/%	K_y/MPa^{-1}	a	b	r
Guandi	10.1	1.7×10^{-4}	4.21×10^{-5}	0.111249	0.9596
Malan 2#	5.4	6.2×10^{-4}	2.3×10^{-4}	0.087522	0.9956

The Table 2 shows that the longitudinal wave velocity fitted by the formula has a high correlation with stress, which can be used to predict the longitudinal wave velocity of coal under different stress.

5. MECHANISM ANALYSIS OF STRESS INFLUENCING ACOUSTIC WAVE VELOCITY CHANGE OF COAL SAMPLES

Coal and rock mass, as a non elastic medium, its wave velocity is highly influenced by the development degree of the internal pore and fissure. When the coal body is subjected to stress, the partial primary fracture and pore are closed, with the stress increasing, the primary coal, the external cracks and pores are formed, developed and expanded constantly, and finally broke down. Because of the pore in the structure of the coal body, the crack and the new crack have a great influence on the velocity propagation of coal，the characteristics of coal pore and fracture structure are based on analyzing the law of acoustic wave velocity variation under the loading condition of coal body. As shown in Fig.4 The internal structure of coal was studied by scanning electron microscope. From the SEM pictures, it intuitively shows that there is a small amount of micro pores development on Malan 2# coal samples, of which layered structure can be seen obviously; structure of Guandi Coal Samples is relatively entire, and only trace amounts of cement debris existed.

Malan 2# coal



Guandi coal

Figure 4: SEM scanning under the magnifying multiple of 7k

The experimental results show that the longitudinal wave velocity and shear wave velocity of Malan 2# coal and Guandi coal are increasing with the stress increasing. This is mainly because the porosity decreases with the stress increasing, and causing the elastic deformation of the particles, the increase of the contact area between particles and the wave velocity of the particles. But at the same time, due to the coal and rock mass consisted of a number of different structures mutual cementation, and structural surface was formed in the interface of structure, which cause wave velocity decayed in the coal. Under the action of stress, these structural morphology and structural plane will be deformed and damaged, which will change the direction of acoustic wave propagation and increase the acoustic attenuation characteristics. And when the sound waves propagate in the coal and rock mass and encounters a structural morphology or structural plane, for example, the crack and crack development of the place, due to the presence of a certain reflectivity difference between the interface and the air, the sound wave in the transmission occurs at the same time, there will be some reflection and refraction. If the size of the pore is similar to the wavelength of the sound wave, or the difference is very large, the acoustic diffraction phenomenon will occur. And when the fissure is filled with the other phases of matter, the transmitted wave will occur to different degree of attenuation of energy. But before the destruction of coal, the increase of the velocity is larger than the decrease of the wave velocity. Therefore, the increase of the wave velocity is shown on the macroscopic. When the coal body stress reaches the peak value, the fracture in the coal seam is rapidly diffused, with the porosity increasing, the wave velocity decreased greatly.

6. CONCLUSIONS

(1) In the course of full stress and strain of coal loading, the longitudinal wave velocity increases firstly, and then decreases when the coal body broke, and the shear wave velocity also increases firstly, but when the coal body breaks, the shear wave signal disappears.

(2) Stress-strain curves of samples have an high consistency on the stress-wave velocity curve, which suggests that the wave velocity can be as the index of reflecting longitudinal wave velocity variations of coal and rock mass stress and the deformation of the internal structure, specially, velocity variations of longitudinal wave can be as a good evolution index of reflecting stress state of the deformation of internal structure.

(3) The relationship between the stress and the longitudinal wave velocity of coal is based on the change of the pore structure of the coal body, which can predict the longitudinal wave velocity of coal body under different stress states.

(4) With stress changed, the variation of acoustic velocity is increased mainly because that the effect of the wave velocity increasing is larger than the effect of the wave velocity decreasing before the destruction of coal, but the large increase of pore closure caused the wave velocity decreased largely after stress peak of coal body up to its peak.

7. ACKNOWLEDGEMENTS

This research is supported by National Natural Science Funds of China (51304212), Fundamental Research Funds for the Central Universities (2009QZ09). The authors would like to express their gratitude to the foundation.

8. REFERENCES

Chen X., Sun J. Z., Tan C. S. (2010). Relation between P-wave velocity and stress of rock samples and their unloading effect, Chinese Journal of Geotechnical Engineering, Volume 32, No. 5, pp. 757-761

Christensen N. I. (1965). Compressional wave velocities in metamorphic rocks at pressures to 10 kilobars, Journal of Geophysical Research, Volume 70, No. 24, pp. 6147-6164

Din W. X. (1997). A recent study on the relation between elastic wave velocity and stress of rock (rock mass), Journal of Geological Hazards and Environment Preservation, Volume 8, No. 3, pp. 43-47

Freund D. (1992). Ultrasonic compressional and shear velocities in dry clastic rocks as a function of porosity, clay content, and confining pressure, Geophysical Journal International, Volume 108, pp. 125-135

Gong S. Y, Dou L. M., Xu X. H. (2012). Experimental Study on the Correlation Between Stress and P-Wave Velocity for Burst Tendency Coal-Rock Samples, Journal of Mining & Safety Engineering, Volume 29, No. 1, pp. 68-70

Huang C. X. (1991). Study on elastic wave velocity of rock under confining pressure, Chinese Journal of geotechnical engineering, Volume 13, No. 2, pp. 32-41

Jiang D. Y, Chen J., Liu J. P. (2009). Experimental research on acoustic and dissolved properties of stress damaged salt rock, Rock and Soil Mechanics, Volume 30, No. 12, pp. 3569-3573

King M. S., Chaudhry N. A., Shakeel A. (1995). Experimental ultrasonic velocities and permeability for sandstones with aligned cracks, International journal of rock mechanics and mining sciences & geomechanics abstracts, Volume 32, No. 2, pp. 155-163

Liu S. D and Cheng X. F. (1999). Acoustic wave detection technology in mining, The Sixth National Academic Conference on Mining, Weihai, pp. 107-110

Luan G. T. and Hu Y. L. (1985). Effect of moisture on the longitudinal wave velocity of rock, Chinese Journal of geotechnical engineering, Volume 7, No. 5, pp. 80-84

Meng Z. P. and Zhang J. C. (2006). Joachim Tiedemann. Relationship between physical and mechanical parameters and acoustic wave velocity of coalmeasures rocks. Chinese Journal of Geophysics, Volume 49, No. 5, pp. 1505-1510

Meng Z. P., Liu C. Q., He X. H. (2008). Experimental research on acoustic wave velocity of coal measures rocks and Its Influencing Factors, Journal o f Mining & Safety Engineering, Volume 12, No. 4, pp. 389-393

Nur A. (1997) Effects of stress on velocity anisotropy in rock with cracks, Journal of Geophysical Research, Volume 76, No. 8, pp. 2022-2034

Peng S. P., Xie H. P., He M. C. (2005). Experimental study on velocity characteristics of lithofacies transition rock mass, Chinese Journal of Rock Mechanics and Engineering, Volume 24, No. 16, pp. 2831-2837

Shi G., Shen L. D., Wang J. X. (2004). Study on Compaction Effect of Rock Sonic Wave, Acta scientiarum naturalium niversitatis pekinensis, Volume 40, No. 2, pp. 177-183

Tao Y. Q., Xu J., Peng S. J. (2010). Yuan M. Experimental study of influencing factor of porosity and effective stress of gas-filled coal, Rock and Soil Mechanics, Volume 31, No. 11, pp. 3417-3422

Wang H. T. and Xian X. F. (1988). The study on characteristics of elastic wave propagation in rocks under complicated stress states, journal of Chongqing university, No. 5, pp. 104-112

Xu X. L, Zhang R., Dai F. (2015). Effect of coal and rock characteristics on ultrasonic velocity, Journal of China Coal Society, Volume 40, No 4, pp. 793-800

Zhao M. J. and Wu D. L. (1999). Ultrasonic velocity and attenuation of rock under uniaxial loading, Chinese Journal of Rock Mechanics and Engineering, Volume 18, No. 1, pp. 50-54

Zheng G. P., Zhao X. D., Liu J. P. (2009). Experimental Study on Change in Acoustic Wave Velocity When Rock Is Loading, Journal of Northeastern University(Natural Science), Volume 30, No. 8, pp. 1197-1200