Experimental investigation of shock pulses in the piston–bit system in interaction with rock mass

VP Efimov* and LV Gorodilov
Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
E-mail: *efimov-pedan@mail.ru

Abstract. The paper presents a measurement procedure for accelerations generated in the piston–bit system in interaction with rock mass. The acceleration oscillograms are analyzed. The quantitative estimates of shock pulses are discussed with regard to their influence on fracture performance.

1. Introduction
Fracture of rocks by impact is a common practice in mining, for example, in cutting (by hammer attachment [1], cutting-type bucket shovel [2, 3] in open pit mining and cutting-type ploughs in underground mining [4]), or in rotary drilling [5]. The review of the research in the related area of science [5–8] shows that the process of rock fracture by different-shape solid indenters has been sufficiently described qualitatively by now, and the appropriate empirical formulas and mathematical models are constructed. In the mean time, it is required to analyze the process of impact fracture with regard to dynamic properties of percussive systems of mining machines. There are no infallible design procedures for the piston–bit systems to be maximum effective in specific-type rocks. Thus, high-performance impact machine engineering in mining is faced by many deterrents.

Naturally, shock pulses generated in the percussion system of a mining machine are governed by the dynamics and designs of the piston and bit, as well as by the properties of rock mass and, consequently, the mechanism of fracture. All these factors in the aggregate define efficiency of rock fracture. Many researchers in Russia and abroad engaged themselves with the subject of shock pulses generated and transferred in percussion systems [1, 9–14]. The research findings are mostly applicable to drilling which uses long drilling tool (drill column) and, consequently, the conditions of shock pulse generation are different.

On the whole, the researchers aim to correlate parameters of a percussion system (piston and bit), properties of rock mass and their interaction performance. These studies lack validated experimental procedures capable to determine the fracture characteristics of rocks under percussion by a bit and the force characteristics of the bit penetration. In this respect, it is expedient to study shock pulses generated in bit, to compare the shock characteristics with fracture process performance and to optimize the shape and size of bits toward higher performance fracture. This paper presents some experimental results on impact testing of marble block by the piston–bit system, and discusses generation and transfer of shock pulses.
2. Experimental procedure

The detailed description of the experimental procedure with recording of pre-blow velocity of piston and accelerations of piston and bit in different materials, including marble blocks can be found in [15]. The test installation presented a pendulum hammer with piston and bit, and rock mass was simulated by a marble block $0.95 \times 0.95 \times 1.5 \text{ m}^3$ in size and 400 kg in weight. The experimental design is shown in Figure 1.

![Experimental design](image)

**Figure 1.** Experimental design: 1—marble block; 2—bit; 3—piston; 4—vibrator inverters AR33; 5—velocity control sensor IDS-2; 6—light sensor for pre- and post-blow bit velocity (two laser–photo diode sensors); 7—amplifiers Bruel&Kjaer 2651; 8—AD converter L-Card E-440; 9—PC.

In the tests, piston 3 was speeded up to a preset velocity $v_1$ (maximum velocity of 7 m/s) up to contact with bit 2. Bit 2 was reliably pressed by a sufficient force to marble block 1.

The test cylindrical pistons had weights of 3.1, 5 and 16 kg and 565 mm long, and the bits 5 and 9.6 kg in weight and 160 mm long had a tapered form, with a taper having length of 30 mm and angle of $60^\circ$ [16]. Accelerations in the piston and bit were recorded using GlobalTest vibrator inverters AR33 and amplifiers Bruel&Kjaer 2651. The sensors were mounted in machined gutters made in the piston and bit. The total measurement error included the constant error (signal–noise inversion) and random error, and was not higher than 5.5% [15]. The velocity control was performed using induction velocity pickup IDS-2 arranged on the piston. The optical sensor (two laser–photo diode pairs) recorded positions of the piston before and after the contact with the bit to determine the pre- and post-blow velocities of the piston, its recovery factor and energy transferred to the bit. The signals were transmitted from the sensors via AD converter L-Card E-440 to personal computer and processed in PowerGraph 3.3.

3. Results and discussion

Figure 2 shows an oscillogram after processing in PowerGraph 3.3.

The integrated signals from sensors of piston and bit accelerations inform on the velocities of these tools. The momentum transferred to a tool and recorded by pickup IDS correlates well with the momentum calculated as an integral of the first acceleration half-wave from the sensors arranged on the bit. The readings of the optical velocity sensor and the piston velocity calculated by integrating of the signals from the acceleration sensor set on the piston also coincide.

Figures 3 and 4 show the superimposed oscillograms from the acceleration sensors mounted on the piston and bit at the distances of 300 and 70 mm from the piston–bit interaction plane, and the velocity curves obtained by integrating. For better visualization, the signals from the acceleration sensor and the piston velocity curves are shifted leftward along the axis $t$ so that the moments of arrival of their shock pulses coincide.
Figure 2. Oscillograms of signals in PowerGraph 3.3 (top downward): accelerations of piston, $a_S$, and bit, $a_l$, measured by sensors AE33, piston velocity $v$ (sensor IDS-2), optical sensor signal $s_O$.

Figure 3. Superimposed oscillograms of piston accelerations $a_S$ (-----) and bit accelerations $a_l$ (——) in the tests of 8 blows (top downward) with bit 5 kg in weight and pistons having weights and pre-blow velocities as follows, respectively: (a) 3.1 kg and $\sim$ 5.01 m/s; (b) 5.5 kg and $\sim$ 4.01 m/s; (c) 16 kg and $\sim$ 2.25 m/s.
Figure 4. Velocity curves obtained by integrating of oscillograms from Figure 3 for piston (……..) and bit (———) in the tests of 8 blows (top downward) with bit 5 kg in weight and pistons having weights and pre-blow velocities as follows, respectively: (a) 3.1 kg and ~ 5.01 m/s; (b) 5.5 kg and ~ 4.01 m/s; (c) 16 kg and ~ 2.25 m/s.

The curves in Figures 4a–4c (top downward) are obtained from test series of 8 blows delivered by pistons of different weight at the same point of bit 5 kg in weight pressed to the block. Pre-blow velocities of the pistons were selected so that their blow energies were approximately equal at different weights of the pistons. The pre-blow velocities of the pistons were non-zero (they were calculated by the piston passes by the marks of the optic sensors), and they were added to the velocities obtained after integrating.

The analysis of the oscillograms of the piston and bit accelerations after their superimposition by the arrival times of shock pulses (Figure 3) shows that:

— at the increased weight of the piston, at the equal energy, the duration of the 1st acceleration halfwave grows both for the piston and the bit. The duration of the piston–bit contact grows in proportion to the reduced weight of the colliding bodies as the contact duration estimated by Hertz’s theory [17];

— since the time $t \geq 0.3–0.4$ ms, intense oscillations of accelerations arise in the bit, which can be induced by cracking in the block;

— after the 1st halfwave, there is an area (more distinct in the oscillogram of blow by piston 16 kg in weight) with closely equal accelerations of the piston and bit;

— the highest efficiency of fracture is observed in the piston–bit pair with weight of 5.5–5 kg (the cut depth $h = 7.06$ mm is higher by 1 and 1.5 mm than in case of the piston–bit pairs with weights of 3.1–5 and 16–5 kg, respectively). The first halfwave in the pairs with weights of 5.5–5 and 3.1–5 kg is ragged and has two humps, and the accelerations in the bowl nearly vanish.

The similar analysis of the velocity curves superimposed by the arrival times in Figure 4 shows that:

— only a few of the bit velocity curves have a positive halfwave transiting to the negative value domain. Probably, this is connected with incorrect experimental data, the so-called ‘zero displacement effect’ in recording of shock pulses by piezoelectric accelerometers, which is particularly distinct in integrating;
— the lightest piston (3.1 kg) has the highest recoil and the weakest fracture efficiency. The other two pistons have small recoil, which governs the high energy transfer coefficient to the bit. For another thing, these two pistons show essential difference in time of the energy transfer. The moment of the velocity transition to the negative value domain is 0.1 ms for the piston 5 kg in weight and to 0.6 ms for the heavier piston;

the motion patterns of the pistons 3.1 and 5.5 kg differ qualitatively from the motion pattern of the piston 16 kg in weight. In the former case, there are oscillations with a period coinciding with the double wave travel in these pistons; in the latter case, such oscillations are almost invisible.

4. Conclusions
This paper has presented the procedure and results on measurement of shock pulses in the piston–bit system in interaction in rock mass. The obtained data exhibit some features of shapes and values of accelerations and velocities of the shock pulses generated in the percussion system in its interaction with marble block, and their correlation with the cut sizes. Further improvement of the procedure will enable a more comprehensive insight into the interaction between the percussion system design variables, shock pulses and the sizes of the cuts made.

The theoretical analysis of the piston and bit motion during shock interaction with rock mass and propagation of shock pulses in them is required to characterize motion of the bit tip as it conditions formation of the loose cuts and to compare the actual and calculated wave patterns.

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