Computer simulation of energy release modes in discharge channel and its influence on stress-strained state formation in solid material under electro-blasting technology

A S Yudin, N V Voitenko and N S Kuznetsova

Tomsk Polytechnic University, Lenina av. 30, Tomsk, 634028, Russia

E-mail: tevn@hvd.tpu.ru

Abstract. In an electro-blasting technology for the solid destruction, the pulse power generators with different types of switches is used. One of them is a triggered vacuum switch, that for an easy operation, has a suitable lifetime of 10^4–10^5 commutations in average and can pass about 100 coulombs of charge. However, in most cases it passes only a half-cycle of the current in the ringing mode operation. In this paper, the influence of the ringing current pulse duration on the stress-strained state formation is investigated. Simulation results of the energy release modes in a discharge channel are given. The crowbar mode of operation is also investigated and a comparison with the ringing mode are presented. It is shown that in a dumping oscillations mode with a damping factor of about 7, the second and the subsequent oscillations contribute only about 5 % of a total energy into the shock-wave.

1. Introduction

An electro-blasting technology and its pros and cons, in comparison with traditional approaches for the rock and the concrete destruction and demolition, have been extensively described in the literature [1-4]. To produce a blast effect, the underwater electro-discharge wave dynamics principles [5, 7] and the high current generators are employed. A common high current generator is a capacitor bank electrical energy storage with a charger, a commutator, and a triggering unit. But under closer examination, there is a certain difference in the topology of circuit diagrams. As we know from the network analysis, the R-C-L circuit could release its energy in three different modes: the discharge with damping oscillations, the discharge without oscillations, and the critical mode. There are various types of capacitors and switches to consume all the stored energy in a most efficient way. It should be noted, however, that the formation of a steep current front, which can be obtained only in the damping oscillation mode, is preferable in the electro-blasting technology, which needs the high pressure pulse generation. The higher the initial pressure pulse, the better the blasting efficiency [8]. In the damping oscillation mode, it is better to use the switches that can pass all current oscillations, for example, the high pressure gas switches or the implement crowbar mode.

In this paper, an attempt to estimate the influence of the second and the subsequent current oscillations on the shock-wave dynamics and the tensile stress state is made. A comparison with the crowbar mode is also given.

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2. Mathematical model description

In this study, the 1D model of the electro-burst is implemented. A complete description of the model is given in [7]. The model involves the transient process equations for the R-C-L circuit (figure 1), the discharge channel energy balance equation, the hydrodynamic equations of wave disturbances description, the plasma channel, and the surrounding medium state equations.

The processes of electrodynamic oscillation in the R-C-L circuit were characterized by the voltage balance equation (taken from the Kirchhoff's laws):

$$L\frac{di(t)}{dt} + (R_{ch} + r)i(t) + \frac{1}{C}\int_0^t i dt = U_0 \,, \tag{1}$$

where: L is the circuit inductance, H; R_{ch} is the channel resistance, Ω; $i(t)$ is the circuit current, A; U_0 is the initial voltage of the capacitor, V; r is the active resistance of the generator, Ω.

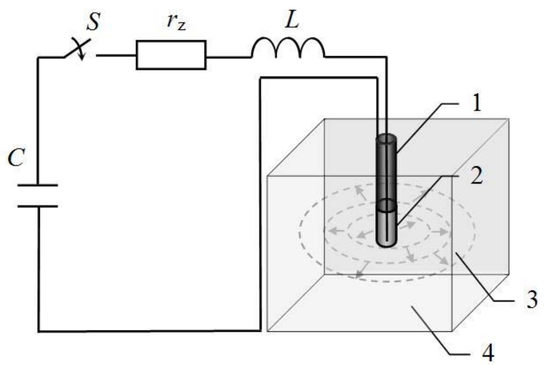

Figure 1. The scheme of shock-wave action on the system of water–concrete under electro-blast: 1 – coaxial cable, 2 – electro-discharge system, 3 – shock-wave disturbances, generated due to expansion of the discharge channel, 4 – destructible material

The current and the voltage waveforms vs time have been calculated with the help of equation (1) along with the empirical equations for the plasma channel resistance $R_{ch}(t)$ which is defined via the integral of a current action in the form of Weizel–Rompe [9]:

$$R_{ch}(t) = K_{ch} \cdot l_{ch} \left(\int_0^t i^2(t)dt\right)^{-\frac{1}{2}}, \tag{2}$$

where: K_{ch} is a spark constant [10].

Electrical plasma channel energy conversion into the plasma energy and mechanical work, performed by the expanding plasma channel:

$$\frac{1}{\gamma-1}\frac{d}{dt}(P_{ch}V_{ch}) + P_{ch}\frac{dV_{ch}}{dt} = i(t)^2 R_{ch} \,, \tag{3}$$

where: γ is the effective ratio of specific heats; P_{ch} is the channel pressure, Pa; $V_{ch} = \pi r_{ch}(t)^2 l_{ch}$ – channel volume, m^3; r_{ch} and l_{ch} are the channel radius and length respectively, m.

The wave propagation is based on a system of the equations including the differential equations of laws of the mass conservation, the momentum, and the energy in the adiabatic approximation, the equations of the media and the plasma state, the correlation of the stress tensor, the spherical tensor and the deformation deviator, equations of the wave dynamics [7]. Kirchhoff's equations and the power balance equation of the discharge channel were jointly solved with the state equations of the surrounding medium, the equations of the continuity, the internal energy, the rations for the components of the stress deviator. The system of equations describing the evolution and the dissipation of shock-wave disturbances was solved self-consistently and approximated by the difference scheme, according to Wilkins method [11].

On the basis of the described equations, the numerical algorithm and the software were developed that allowed us to carry out the electro-blast computer experiments in the water–concrete condensed media.

3. Calculation results of tensile stress state at different modes of current oscillations

The computer simulations were made under the conditions listed in tables 1–3.

Table 1. Electric parameters of simulation.

U_0, kV	L, μH	r, mΩ	C, μF	l_{ch}, *cm*	γ	K_{ch}, V·s$^{0.5}$·m^{-1}
13	1.5	0.022	1120	9	1.26	210

Table 2. Parameters of concrete.

ρ, g/cm^3	*μ*, GPa	Y_0, MPa	α, m/sec	b
2200	17	77	2330	1.51

Table 3. Parameters of borehole filling media (polyethylene).

ρ, g/cm^3	α, m/sec	b
940	2900	1.48

The four operating modes were compared with each other: 1) – the half period mode; 2) – the one period mode; 3) – the one and a half period mode; 4) – the crowbar mode. These are the typical modes realized in our experiments, except the crowbar mode.

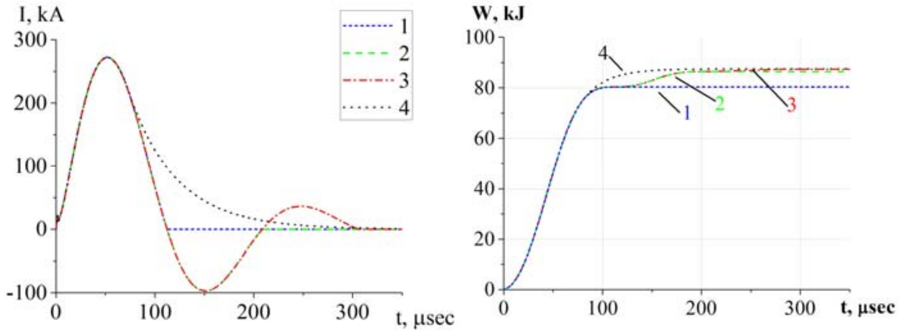

Figure 2. The current and energy curves: 1) – the half period mode; 2) – the one period mode; 3) – the one and a half period mode; 4) – the crowbar mode.

The analysis of the shock-wave dynamics have shown that the discharge channel emits the intense wave disturbances only at an initial phase of its expansion, and the main fraction of the energy is released in the first oscillation of the current. The second and the subsequent oscillations have a little effect on the energy of the shock-wave. The graphs show that in the modes with two and three current oscillations, 9 % and 10.2 % more energy is released, respectively, in relation with the mode 1). Before the time point of 100 μsec, when there is no difference in the energy input (figure 2), there is no difference in the tangential tensile stresses as well (figure 3, 100 μsec). After 200 μsec, when the shock-wave comes to the free border, in the modes 2) and 3), the tangential tensile stress become higher, up to 5% in average (figure 3, 200-900 μsec), that is evidently caused by an addition of the energy from the buttery storage. One can see that a tensile stress amplitude is greater and acting longer in time, if the energy from the generator continue to release in the discharge channel (figure 3, the modes 2), 3) and 4)). A comparison of the ringing mode with the crowbar one shows that in the crowbar mode, there is no significant differences in the tangential tensile stresses for a corresponding time interval, except the time points of 400 and 900 μsec, when the stress reaches up to 5% over the magnitude in the relation of the ringing mode with two and three half-waves of the oscillation (figure 3, 400, 900 μsec). So, this mode could be preferable in a pulse power technology for the rocks and concrete destruction, but its implementation involves either an extra spark gap switch or a semiconductor rectifier, that actually is more complicated.

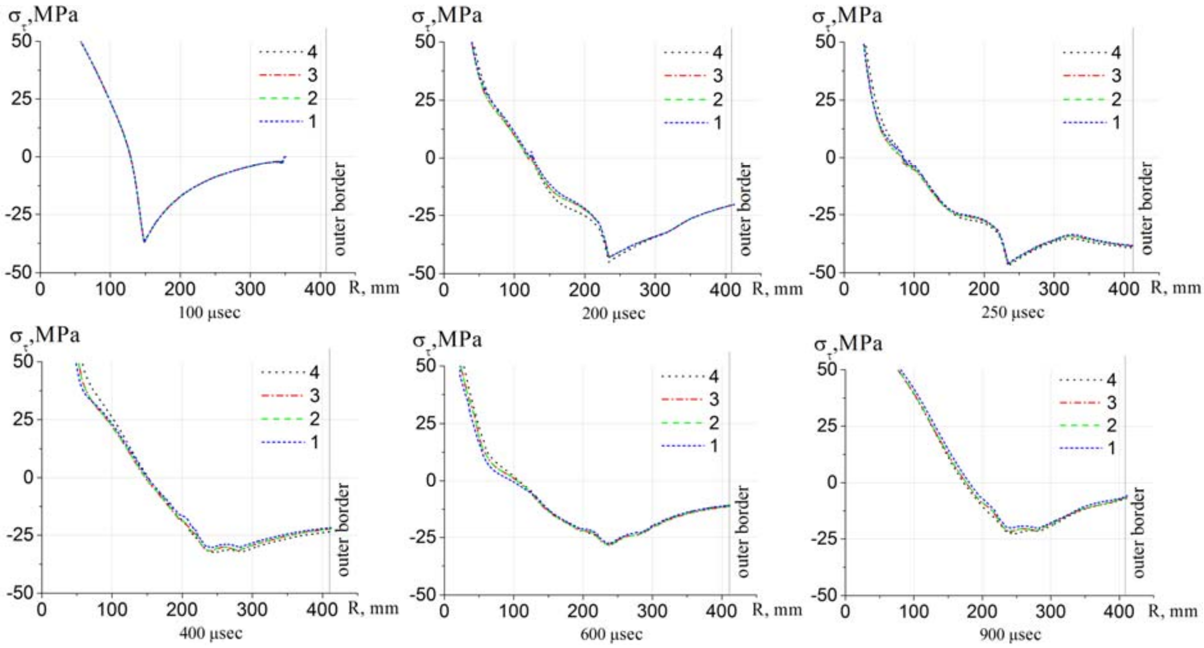

Figure 3. Distribution diagrams of tangential stresses in the pressure wave in a concrete at time of 100, 200, 250, 400, 600 and 900 μsec, R – a radial distance from the discharge channel.

4. Conclusion

The data obtained in this research show that the crowbar mode is preferable in the pulse power technology for the rocks and concrete destruction. It should, however, be admitted that a system with one commutator, for example the trigatron or the TVS, is more simple in technical implementation. Moreover, the crowbar mode gives only about 10% profit in the tensile stresses in comparison with the half wave ringing mode with a damping factor of about 7 that can be easily realized with the TVS. In some cases, the loss of 10% of the energy is not so high price for a simplicity of the entire pulse power system.

Despite the ability of the TVS to recover, in some cases, after 0,5T of current oscillation, it has a low inductance geometry, wide operating voltage ranges, a high current and charge carrying capability. Also, they are extremely robust devices that can survive after an over-voltage, an over-current, and a reverse-current fault which would destroy other types of switching devices. With 10^4–10^5 pulses lifetime these devises have a good application potential for the low pulse repetition rate generators like the pulse power systems designed for the rock fracturing.

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