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Design of Control Circuit for an Electro-Magnetic Gene Gun

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Abstract: - A control circuit of a gene gun, which employs electromagnetic force as power source based on electromagnetic mechanics, is proposed in this paper. In the control circuit, a single capacitor stores energy and instantaneously discharges to an electromagnetic energy device in the gene gun, and thus provides micro-projectiles with electromagnetic force to generate strike force. Discussions in this paper are mainly focused on the control circuit, the strike force generated from the discharge effect of the electromagnetic device, derivative of the electromagnetic strike force theorem, experiments and analysis on each module of the control circuit, and test of an actually built gene gun. This study has disclosed that the proposed electromagnetic gene gun was able to energize micro-projectiles generating strike force as high as 4500psi. The proposed gene gun with broader range of the strike force is apparently better than the third-generation (high pressure gas type) gene guns, with more features including lower cost of manufacturing and convenience of operation. The validness and feasibility of the proposed gene gun have been tested and verified in the experiments.

Key Words: - Electromagnetically Powered, Impulse Force, Gene Gun.

1 Introduction

Gene guns are also called particle guns. During the process of genetic engineering, DNA (Deoxyribonucleic Acid) is first extracted from donor cells. Then by dividing DNA and vectors with restriction enounces, connecting exogenous gene of DNA fragments to carriers with DNA ligase and thus forming molecules of DNA recombination. The molecules of DNA recombination are then delivered into receptor molecules with gene guns where small gold or tungsten particles coated with DNA are accelerated at high speed and then penetrate cell walls and/or cell membranes, thus the DNA are delivered into target cells and the process of gene transfer is completed. In 1987, Prof. John Sanford, (Cornell University, the United States), invented a gunpowder driven gene gun that shot micro-projectiles [1] which was the very first-generation gene gun [1], [2]. Later, the second-generation gene guns, high voltage discharge type gene guns, were developed [3], [4], which utilized high temperature gas (vaporizing a drop of water produced by high voltage discharging) for driving accelerators. The third-generation gene guns were high-pressure gas type gene guns [5]-[14] in which high-pressure helium was often adapted as power source. But the exhaustion of such high-pressure gas might cause additional problems. Furthermore, helium was expensive. A gene gun designed based on electromagnetic mechanics with lower cost and ease of use is to be proposed in this paper..

As mentioned above, the process of gene transfer is the process of delivering exogenous genes into living cell or tissue with high speed “Particles” and keeping the exogenous gene intact. The “Particles” are small sticky gold or tungsten particles with the diameter of 0.4-2.0μm. Because the “Particles” cannot be accelerated directly, they must be attached on projectiles such that the DNA may be accelerated along with projectiles to high velocity and then transferred into acceptors. It is therefore that gene guns are critical technologies in biotech industry.

With a better gene gun, skills for biotechnology may be improved and the probability of success may be increased. But to date, documents on the research and development of gene guns are still rare [1]-[14].

This paper is organized as following. In section 2, theoretical results on electromagnetic impacts are described. In section 3, the basic structure of the control circuit and opperation of the proposed gene gun are introduced. In section 4, design of control circuit. The results of measured impact force of the actual hardware are shown in section 5 which demonstrates the correctness and the feasibility of the control circuit for the proposed gene gun.

2 Electromagnetic Impact

According to the Faraday's law of electromagnetic induction [15], electric energy is induced along with magnetic fields. The relation between voltage V and current I in a circuit may be described by the following equation:

$$V + \wp = I\Re \tag{1}$$

where

$\wp$: Induced voltage,

$\Re$: Resistance in a circuit.

Both the electric charge q and the current I vary with time t and may be expressed as:

$$dq = I\,dt \tag{2}$$

Thus, the relation among the voltage, electric charge, current and time may be further described as:

$$Vdq = VI\,dt = -\wp I\,dt + I^2 R dt \tag{3}$$

According to the Faraday's law of electromagnetic induction:

$$\wp = -\frac{d\Phi}{dt} \tag{4}$$

where

Φ : flux.

Equation (4) describes that the induced voltage equals to the negative time variance of flux in a static close loop. The minus sign in equation (4) guarantees the current induced by the induced voltage flows in a direction against the variance of the flux. Rewrite equation (3) according to equation (4) and then equation (3) may be expressed as:

$$\begin{aligned} V\,dq &= VI\,dt = -\wp I\,dt + I^2\Re dt \\ &= I\,d\Phi + I^2\Re dt \end{aligned} \tag{5}$$

If the flux is invariant, according to Ohm's Law which I and $\Re$ obey, $I^2\Re dt$ is the time variance of electric energy that can be calculated, and $I\,d\Phi$ stands for the energy generated by the circuit. Thus, if $I^2\Re dt$ is not considered, equation (5) may be simplified as:

$$dW_{ex} = I\,d\Phi \tag{6}$$

where

W_{ex} ： energy generated by external power source.

The dW_{ex} in equation (6) may be positive or negative. If it is positive, that means the direction of the flux generated by current I and the direction of the current I are identical in the circuit if there's no magnetic hysterics that consumes energy in the circuit, the magnetic energy in the circuit equals to dW_{ex}. Because the magnetic energy varies, it can be applied to circuits for generating force or torque.

Considering the N -turn round coil shown in Fig 1. Let the length from the z-axis to the inner side and outer side of the coil to be b_1 and b_2 respectively, then the flux density B at any point inside the coil may be expressed as:

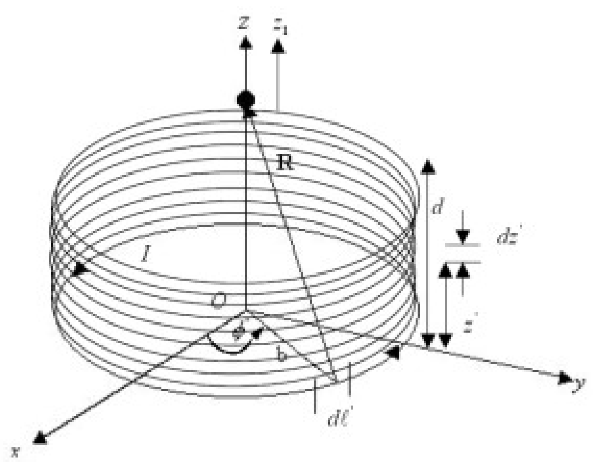

Fig. 1 N-turn round coil with current I

$$B = \int dB$$

$$= \mathbf{a}_z \int_0^d \frac{\mu_0 IN (b_2 - b_1)^2 dz'}{2[(b_2 - b_1)^2 + (z - z')^2]^{\frac{3}{2}}}$$

$$= \mathbf{a}_z \frac{\mu_0 IN}{2(b_2 - b_1)}$$

$$\left[\frac{z \ln\sqrt{z^2 + b_2^2} + b_2}{\sqrt{z^2 + b_1^2} + b_1} - \frac{z_1 \ln\sqrt{z_1^2 + b_2^2} + b_2}{\sqrt{z_1^2 + b_1^2} + b_1}\right] \quad (7)$$

Because the magnetic force $F = q\mathbf{u} \times B$, the magnetic force inside the coil is:

$$\boldsymbol{F} = q\mathbf{u} \times \boldsymbol{B}$$

$$= qu \times \mathbf{a}_z \frac{\mu_0 IN}{2(b_2 - b_1)}$$

$$\left[\frac{z \ln\sqrt{z^2 + b_2^2} + b_2}{\sqrt{z^2 + b_1^2} + b_1} - \frac{z_1 \ln\sqrt{z_1^2 + b_2^2} + b_2}{\sqrt{z_1^2 + b_1^2} + b_1}\right] \quad (8)$$

where

$\mathbf{u}$: velocity of moving electric charge.

Equation (8) means the moving electric charge generates current and the current generates magnetic field, thus the current is generated along with the magnetic field. Further, force F may also be expressed as:

$$F = m\mathbf{a} = m\frac{d\mathbf{u}}{dt} \quad (9)$$

where

m ：velocity of matter;

$\mathbf{a}$ ：acceleration.

By combining equation (8) and equation (9), equation $m\frac{d\mathbf{u}}{dt} = q\mathbf{u} \times B$ is derived. If the mechanics model shown in Fig. 2 is further analyzed, the total force F may be expressed as:

$$F = F_1 - F_2 = m\frac{d^2\mathbf{u}}{dt^2} \quad (10)$$

where F_1 and F_2 are forces applied on the two poles of the element.

The above equation describes that while the impact force F_1 is induced by the electromagnetic coil, an opposite magnetic force F_2 is also developed, thus the total impact force generated is $F_1 - F_2 = m\frac{d^2\mathbf{u}}{dt^2}$.

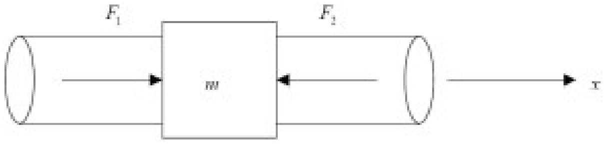

Fig. 2 Mechanics model device

3 Structure of the Control circuit and Opperation

3.1 Structure of the Control circuit

The control circuit of the gene gun, incorporated with an external circuit and a microcomputer, drives the electromagnetic energy device. The gene gun utilizes a capacitor (6800μf/400V) to store energy and to discharge to the electromagnetic coil in a very short time, such that a strong impact force is generated. The external circuit comprises an AC current source, a DC current source, a plurality of photoelectric interfaces, and a plurality of energy storing capacitors, a solid-state switch circuit, a zero voltage control circuit, a voltage control circuit, a voltage comparator circuit and an electric energy compensation circuit. Fig. 3 shows a block diagram of a control circuit of the proposed gene gun, wherein a microcomputer is adapted to control the output impact force such that a series of different or identical impact force may be generated which solves the problem of the conventional single shot gene guns of insufficient impact force and narrow time division.

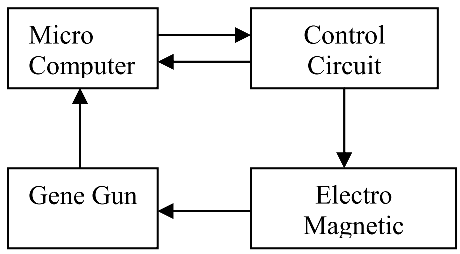

Fig 3 Structure of the control system of the gene gun

3.2 Opperation

Fig. 4 shows a block diagram of a charge/discharge circuit for a DC power source. In this figure, DC power is stored in the energy storing capacitor and then discharged to the electromagnetic coil to make the soft iron stick work. While switch 1 S1 is ON, the energy from DC power source 1 is stored in energy storing capacitor 2. While switch 1 S1 is switched from ON to OFF and switch 2 S2 is switched from OFF to ON, the energy storing capacitor 2 discharges to the voltage dividing resistor 3 and the voltage dividing resistor 4, and turns on the SCR 6 by triggering its gate. Thus, the energy storing capacitor 2 discharges to the coil 5-1 of the electromagnetic device 5. With the charge/discharge mechanism of the energy storing capacitor in the DC power charge/discharge circuit shown in Fig. 4, wherein the energy storing capacitor 2 discharges to the coil 5-1 of the electromagnetic device 5 and make the soft iron stick 5-2 work, the object of discharging to the electromagnetic coil after storing DC power in the energy storing capacitor is achieved.

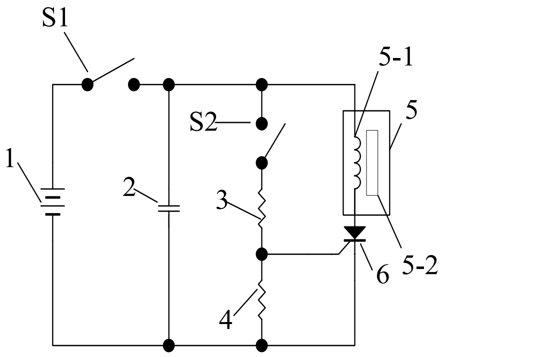

Fig. 4 Charge/discharge circuit for DC power source

4 Design of Control Circuit

Fig. 5 shows the control circuit A of the gene gun and Fig. 6 shows the control circuit of the gene gun with microcomputer activated electric energy compensation circuits and photoelectric interface circuits. Combining the circuits in Fig. 5 and Fig. 6, a complete circuit designed to store energy and discharge the stored energy to an impact device with multiple sets of capacitors is completed. Wherein the circuit comprises:

(a) A DC power source circuit for generating a 12V output and a 5V output.

(b) A voltage zero-crossing control circuit for overcoming EMI problems and to precisely control the programmable trigger time with sinusoidal zero-cross signals.

(c) A power source control circuit for ceasing the voltage zero-crossing control circuit.

(d) A voltage comparator circuit operating in cooperate with the power source control circuit for ensuring the security of the control circuit of the gene gun at high voltage and the quality of the circuit at low voltage.

(e) An electric energy compensation circuit for compensating the insufficient discharge energy of the breaking energy while discharge gaps are developed for continuous charge/discharge of the capacitors.

(f) 4 sets of solid-state switch circuits for generating output of electromagnetic force operating in cooperate with a single set of photoelectric interface. The top margin should be 30mm and the bottom margin should be 25mm.

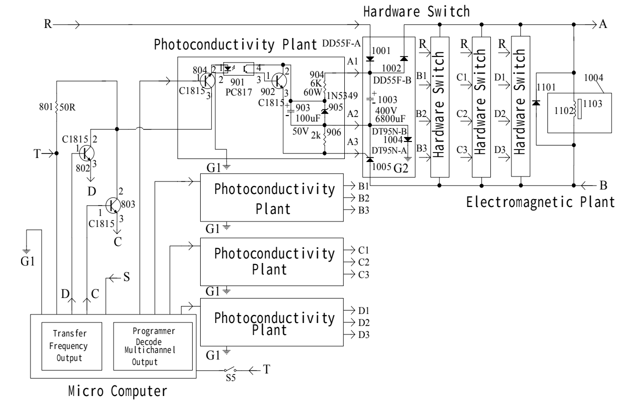

Fig. 5 Control circuit A of the gene gun.

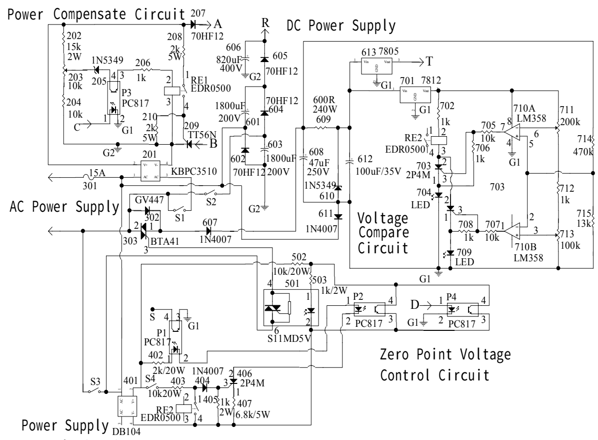

Fig. 6 Control circuit B of the gene gun

5 Results of the Experiments

According to the characteristics of the circuit and the design considerations, an electromagnetic gene gun was constructed. The internal structure of an electric tacker bought at the market was modified and adapted as an impact device of the gene gun. Inside the modified electric tacker, a 6800μF/400V capacitor was adapted to store energy and discharge to an electromagnetic device in a very short time, thus provided projectiles with electromagnetic energy to generate impact force. The accuracy and feasibility of the gene gun proposed according to the theory analysis in this paper was examined by comparing with the pressure data in the protocols of market available gene guns. The specifications of the proposed gene gun are:

Input: AC 110V,

Capacitor: 6800μf/400V,

Impact device：internal resistance of the coil: 0.68Ω,

Inductance: 3.07mH

A piezo-type force sensor manufactured by KISTLER was utilized as a measurement unit. The voltage signal generated by the force sensor was amplified by a charge amplifier and transformed into the form of impact force. Table 1 shows the impact force measured by the force sensor at different capacitors and different discharge voltages. Fig. 7 shows the chart of pressure per unit-area according to the data shown in Table 1, wherein the unit of pressure is PSI, the discharge voltage of the capacitor is at the x-axis and the impact force of the gene gun is at the y-axis. As shown in this figure, the curves of impact forces developed by different capacitors are similar except for the discharge voltages for maximum impact forces. The smaller the capacitor is, the higher the discharge voltage is required for identical impact forces. The impact forces are about in direct proportion of the discharge voltages. With identical discharge voltages, larger capacitors generate more impact forces. For smaller capacitors, discharge voltages must be raised to generate more impact forces. While the discharge voltage is greater than a certain value, the output impact force decreases instead because a force pulls the soft impact iron back while it is inserted into about 1/3 of the solenoid. Such phenomenon is found at lower voltages in bigger capacitors.

Table 1 Measured impact forces

Discharge Voltage (V)	Force Measure Voltage (V)
40	0.74
50	1.96
60	2.14
70	2.72
80	5.2
90	6
100	6.8
110	8.5
120	8
130	2.4
140	2
150	1.84

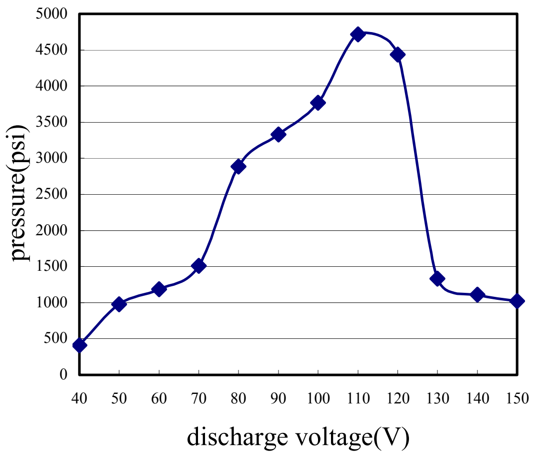

Fig. 7 Discharge Voltage-Pressure Diagram

Several protocols [16] for gene guns are shown in Table 2. Comparing the data shown in Table 2 with the capabilities of the proposed gene gun, the average range of the pressure in practical applications utilizing gene guns is about 650~2000psi, while the proposed gene gun has a maximum impact force of at least 4500psi, which is far beyond the pressure required for most applications of gene transfer. The proposed gene gun has the capability to provide a wide range of impact force, which apparently overtakes gene guns at the market and may further be modified as a hand-held type gene gun.

Table 2 Protocols of gene gun [16]

Floristic component	Cellulary tissue	Pressure (PSI)
Cassava	Callus	900-1100
Cotton	Seed	1100
Groundnut	Stem	900-1500
Maize	Callus	650
Maize	Immature embryo	1100
Rice	Callus	1300
Sunflower	Callus	1550
Tobacco	Leaf	1100
Tobacco	Cell suspension	1100
Tobacco	Leaflet	1100
Tobacco	BY-2 cells	1100
Mustard	Leaf	1100
Wheat	Immature embryo	1100
Oat	Callus	1100
Long-leaf southern pine	Callus	1100
Eastern white pine	Callus	1100
Millet	Callus	1300

6 Conclusion

A novel gene gun developed based on electromagnetic mechanics has been proposed in this paper. Besides the benefits of lower cost of manufacture and convenience of operation, as we compare the impact force with those of the gene guns at the market, it is found that the average range of the pressure in practical applications utilizing gene guns is about 650-2000psi while the proposed gene gun has a maximum impact force of at least 4500psi that is able to provide a wider range of impact force, which apparently overtakes the third-generation gene guns. The validity and feasibility of the proposed gene gun was tested and verified in the experiments. The gene gun may be further made as a hand-held type gene gun and can be regarded as a prototype for the fourth-generation gene gun.

Acknowledgement

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