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TRANSFORMER-TYPE SEEDING SYSTEM OF A HELICAL FCG BASED ON A TRANSVERSE SHOCK WAVE FERROMAGNETIC GENERATOR

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ABSTRACT

A new application of the effect of transverse-shock-wave demagnetization of $Nd_2Fe_{14}B$ high-energy hard ferromagnets for powering an explosive-driven helical flux compression generator (FCG) is proposed. The novel FCG seeding system based on a compact transverse shock-wave ferromagnetic generator (FMG) containing a 200-cm^3 $Nd_2Fe_{14}B$ energy-carrying element and a 12 g high explosive charge was designed, constructed, and tested. The proposed design is based on the idea that the wide coaxial single-turn pulse-generating coil of the FMG can simultaneously serve as a seed coil for the FCG. The coaxial single-turn pulse-generating coil of the FMG was wound on the initial part of the FCG helix; therefore, only transformer coupling existed between the pulse-generating system of the FMG and the helix of the FCG. This seeding system provides up to 180 A current amplitude and 55 μs current pulse duration to a helical FCG.

INTRODUCTION

A new type of autonomous primary power source that is capable of storing electromagnetic energy for infinite periods and releasing the stored energy in pulses of 5 to 60 μs under the action of high explosives was invented recently [1-8]. These devices are shock-wave ferromagnetic generators (FMGs); their operation is based on the fundamental physical effects of longitudinal [1-3] and transverse [4-8] shock wave demagnetization of $BaFe_{12}O_{19}$ hard ferrimagnets [1,2] and $Nd_2Fe_{14}B$ hard ferromagnets [2-8].

Miniature FMGs are capable of generating both high voltages and high currents and were investigated in detail in previous works [1-8]. Our work demonstrated that individual devices with a total volume of 25 cm^3 are capable of producing current pulses with amplitudes up to 4 kA, and with full width at half maximum (FWHM) of 60 μs.

An autonomous magnetic flux compression generator (FCG) requires a source of primary power (a seed source) to create an initial magnetic field in its operating volume. In [9], we experimentally demonstrated the successful operation of a miniature completely explosive FMG-FCG system. The developed system utilized a multi-turn transverse-shock-wave FMG as the seed source and a helical mini-FCG as the pulsed power amplifier. In this design, we directly connected the two output terminals from the FMG seed source to the two input terminals of the FCG helix.

In the present work, we proposed and developed a new design for a completely explosive FMG-FCG system. It utilizes a single-turn high-current FMG as a seed source and a helical FCG as a pulsed power amplifier. In this system, the FMG seed source is transformer-coupled to the stator of the FCG.

PRINCIPLE OF OPERATION, DESIGN, AND EXPERIMENTAL SYSTEMS

A schematic diagram of the FMG-FCG system we developed for this investigation is in Fig. 1. It contains a transverse high-current FMG and a helical FCG. The FMG incorporates an $Nd_2Fe_{14}B$ hard ferromagnetic energy-carrying element, an explosive charge, two detonators, and a copper single-turn seeding coil. The $Nd_2Fe_{14}B$ energy-carrying element of the FMG is comprised of four identical $Nd_2Fe_{14}B$ hollow ferromagnetic cylinders (each had O.D. = 50 mm, I.D. = 10 mm, h = 25 mm) magnetized along their axes as shown in the figure. The overall dimensions of $Nd_2Fe_{14}B$ energy-carrying element of the FMG were O.D. = 50 mm/I.D. = 10 mm/h = 100 mm, and its total mass was 730 g. The magnetic parameters of the $Nd_2Fe_{14}B$ were: residual flux density, B_r, = 1.23 T, coercive force, H_c, = 8.99 10^5 A/m, and maximum energy product, BH_{max}, = 0.279 J/cm^3.

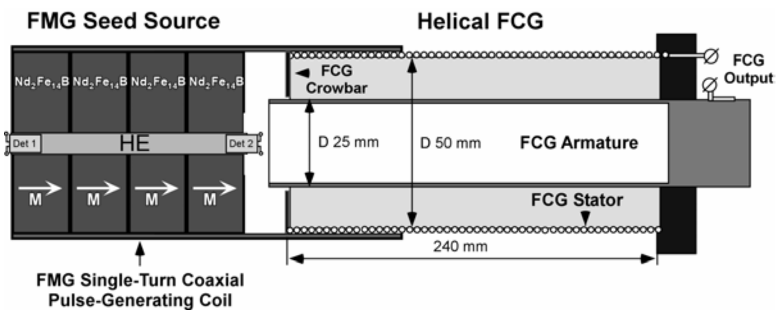

Figure 1. A schematic diagram of the FMG-FCG system.

The operation of the FMG seed source is as follows. The high explosive (HE) charge and two RP-501 bridgewire detonators are located in the central hole of the $Nd_2Fe_{14}B$ energy-carrying element (Fig. 1). After explosive initiation, a transverse shock wave (shock wave propagates across the vector of magnetization **M**) is initiated in the body of the $Nd_2Fe_{14}B$ hard ferromagnetic energy-carrying element. The resulting transverse shock compression of the $Nd_2Fe_{14}B$ hard ferromagnet results in a hard ferromagnetic–to–non-ferromagnetic phase transition in the material [3-8].

As a result of the phase transition, a pulsed electromotive force (EMF), $E_g(t)$, appears in the pulse-generating coil of the FMG in accordance with Faraday's law,

$$E_g(t) = - d\Phi(t)/dt, \qquad (1)$$

where dt is the time it takes for the magnetic flux, $d\Phi(t)$, to change. The EMF pulse causes the current flow in the FMG pulse-generating circuit.

The helical FCG used in the experiments contained a stator, an armature, and a crowbar (Fig. 1). The FCG stator was a multi-turn coil with variable inductance. The I.D. of the stator was 50 mm, the same as the diameter of the ferromagnetic energy-carrying elements of the FMGs. The O.D. of the FCG armature was 25 mm, and the length of the FCG helix was 240 mm.

The electrical parameters of the helix of a typical FCG used in the experiments were as follows: serial inductance L_s(100 KHz) = 56.1 μH, serial resistance R_s(100 KHz) = 0.92 Ω, absolute impedance Z(100 KHz) = 34.2 Ω.

The coaxial seeding system we developed is based on the idea that the pulse-generating coil of the FMG can simultaneously serve as a seed coil for the FCG (Fig. 1). We made the pulse-generating coil as a wide single coaxial turn (copper hollow cylinder). One end of the turn served as the FMG pulse-generating coil, and we wound it around the $Nd_2Fe_{14}B$ energy-carrying element of the FMG. We then wound the opposite end of the hollow cylinder over a portion of the FCG stator (Fig. 1). There was no direct electrical contact between the pulse-generating coil of the FMG and the helix of the FCG; the only coupling between the coils of the two devices was via this transformer coupling.

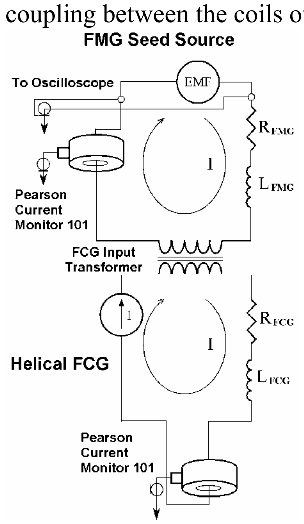

Figure 2. Equivalent circuit diagram of the coaxial FMG-FCG system.

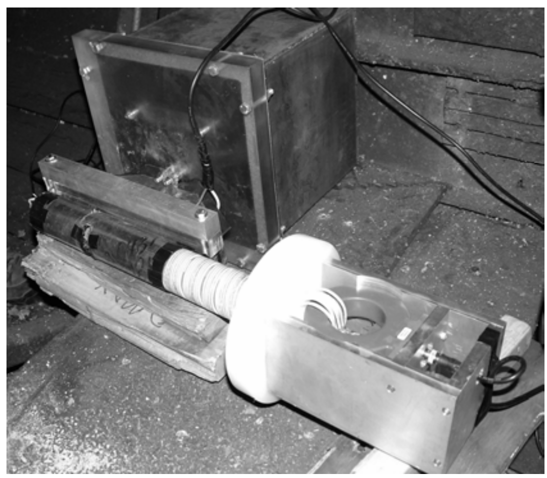

Figure 3. A photograph of the coaxial FMG-FCG system placed in the detonation tank and prepared for explosive test.

The operational principles and equivalent circuit diagram of the coaxial FMG-FCG system are in Fig. 2. A photograph of the system before explosive operation is in Fig. 3. The length of the FMG pulse-generating/seeding single-turn coil was 250 mm, and a 102 mm portion of the left end of the single-turn coil was wound on the $Nd_2Fe_{14}B$ energy-carrying element (Figs. 1 and 2). The distance between the right end of the FMG ferromagnetic module and the left end of the helix of the FCG was 68 mm. A 90 mm portion of the right end of the single-turn coil was wound on the helix of the FCG. In these experiments, we covered most of helix of the FCG (total length 240 mm) with the FMG pulse-generating/seeding coil (Fig. 2).

A schematic diagram of the experimental setup used to investigate the compact coaxial FMG-FCG system is in Fig. 4. In this work, we studied the seeding processes in the coaxial FMG-FCG systems and only loaded explosives into the FMG. We monitored the current in the FCG helix with a protected Pearson 101 current probe placed at the back of the FCG.

The equivalent circuit diagram of the FMG-FCG system and measuring circuit are in Figs. 2 and 4. The equivalent circuit of the FMG seed source contains an *EMF* source, pulse-generating coil resistance (R_{FMG}), and inductance (L_{FMG}). The FMG is connected to the FCG through the FCG input transformer. The equivalent circuit of the FCG contains a helical winding having resistance R_{FCG} and inductance L_{FCG}.

To measure the current evolved from the FMG, the single coaxial turn was connected by a strip transmission line with a current loop to a Pearson 101 current probe placed inside a steel measuring box (Figs. 2-4) that we placed inside the detonation tank. We monitored the voltage across the FMG coil directly with a Tektronix TDS 2024 oscilloscope.

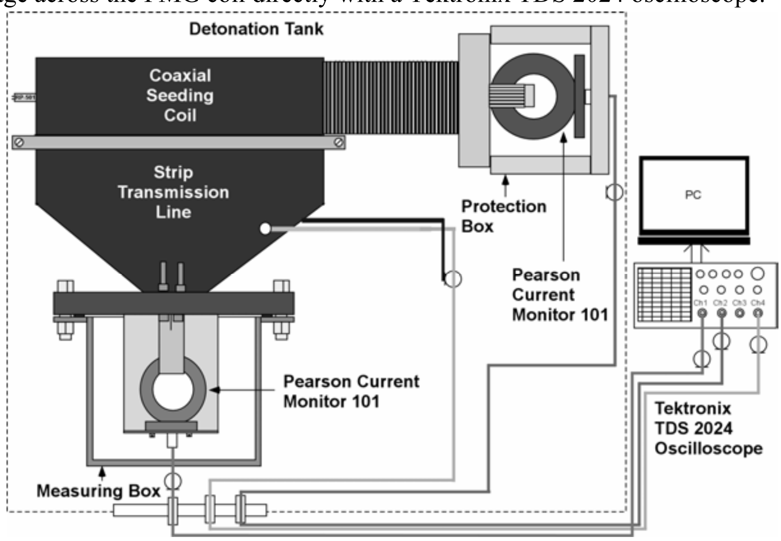

Figure 4. Schematic diagram of the experimental setup used to investigate the seeding process in the coaxial FMG-FCG systems.

We performed the explosive experiments at the Rock Mechanics and Explosive Research Center at the University of Missouri-Rolla.

RESULTS AND DISCUSSION

We performed a series of explosive experiments to estimate the minimum amount of HE charge in the FMG that provided complete demagnetization of the $Nd_2Fe_{14}B$ energy-carrying element. Our results revealed that 12 g of desensitized RDX provides complete "$Nd_2Fe_{14}B$ hard ferromagnet–to–non-ferromagnet" phase transformation of an $Nd_2Fe_{14}B$ energy-carrying element of 730 g mass.

Results obtained for FMG-FCG systems we tested are in Figs. 5 and 6. Figure 5 shows a typical waveform of the current pulse produced in the FCG helix by the FMG seed source. In accordance with Lentz' law, the direction of the current in the FCG helix is opposite to the direction of the seed current in the seeding coaxial single-turn copper coil. The results of our experiments were very reproducible. The average amplitude of the seed current pulse (obtained from 5 explosive experiments) was 174 ± 9 A, and its risetime was 24.7 ± 4.6 μs. The FWHM of the current pulse was 59.8 ± 8.9 μs. The full duration of the current pulse varied from 130 to 140 μs. These experimental results proved the general idea of creation of a coaxial transformer-type seeding system described above.

The corresponding waveforms of the current pulse produced by an FMG (Fig. 4) in the single-turn coaxial pulse-generating/seeding coil, and a voltage across the coil are shown in Fig. 6. The amplitude of the current pulse was 880 ± 30 A, and its risetime was 24.0 ± 4.2 μs.

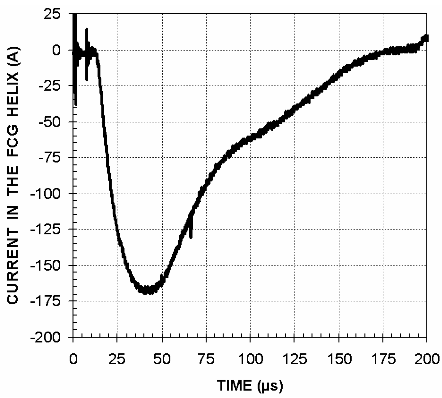

Figure 5. Waveform of the current pulses produced in the helix of the FCG by the FMG seed source.

It can be seen from the experimental data that the rise times for current in the single-turn coaxial pulse-generating/seeding coil (τ = 24.0 ± 4.2 μs) and for the seed current in the FCG (τ = 24.7 ± 4.6 μs) are practically equal. This is additional evidence that coaxial transformer-type seeding systems work as we hypothesized.

The average FWHM of the current pulse [Fig. 6(a)] was 43 ± 5.9 μs, and the full duration of the current pulse was about 140 μs. The noise in Fig. 6(a) is related to the resolution of the oscilloscope.

The amplitude of the FMG voltage pulse [Fig. 6(b)] was -5.2 V, and its τ = 6.2 μs. The FWHM of the voltage pulse was 24.3 μs. The noise at the beginning of the voltage waveform in Fig. 6(b) is related to the detonator initiation signal from our firing unit.

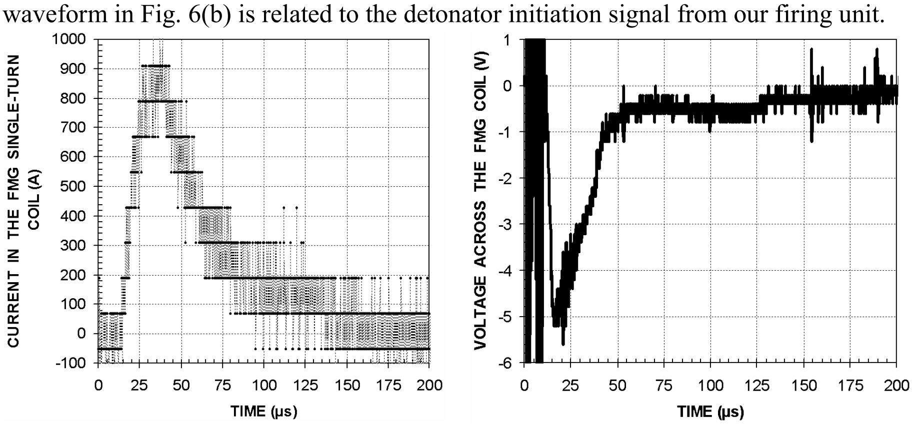

Figure 6. Waveforms of the current pulse produced the FMG seed source in the single-turn coaxial pulse-generating/seeding coil (a) and voltage across the coil.

SUMMARY

We proposed, and experimentally verified, a new application of the physical effect of transverse shock-wave demagnetization of the $Nd_2Fe_{14}B$ high-energy hard ferromagnets: seeding a helical FCG by the operation of an FMG without direct electrical contact between the FMG pulse-generating coil and the FCG helix. The seeding system for a coaxial, completely explosive FMG-FCG system was developed and tested.

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