Demagnetization Process Analysis and Numerical Simulation of Magnet with Shock Wave from Compact Explosively Driven Ferromagnetic Generator

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Abstract. For compact explosively driven ferromagnetic impulse source used in magnetic flux compression generators, the relations between the magnet's demagnetization rate and the shock wave pressure are theoretically analyzed. A nonlinear finite element method is adopted to conduct numerical simulation on the magnet's impact loading process. The propagation rules and pressure distributions of shock wave within hollow cylindrical NdFeB magnet caused by lateral impact of single-ended and double-ended initiators are explored. The numerical simulation results show that, the pressures at both ends resulting from lateral impact of double-ended initiating explosives on hollow cylindrical magnet are low; double-ended initiating has faster demagnetization rate, swifter variation of flux and higher electromotive force of inductive output than single-ended initiating.

1. Introduction
Compact explosively driven ferromagnetic generator is a device that makes use of the impact of ferromagnetics to achieve the transduction from magnetostatic energy to electric pulse energy. As shown in Figure 1, the shock wave driven by the explosion of explosives works on ferromagnet wrapped by conductor coils (magnetization direction M) for rapid demagnetization of magnet. In accordance with Faraday's law of electromagnetic induction, the rapidly changing flux within the conductor coils will produce electromotive force in the conductor, thereby forming pulse current i in the discharge circuit composed by loads and providing pulse energy for post-stage circuits.
Domestic and foreign scholars have explored explosively driven ferromagnetic generator from the theoretical, numerical simulation and experimental perspectives. Authors in [1], [2], [3], [4] theoretically studied the principle of explosive demagnetization of ferromagnet, and carried out experiments on lateral and longitudinal shock waves of explosively driven ferromagnetic generators. Authors in [5], [6] investigated the dynamic features of NdFeB under the shove wave, and analyzed and computed the magnetic-electric conversion principle of explosively driven ferromagnetic generators. Authors in [7] theoretically and empirically studied explosively driven ferromagnetic generators. For compact explosively driven ferromagnetic impulse source used in magnetic flux compression generators, the relations between the magnet's demagnetization rate and the shock wave pressure, as well as the propagation rules and pressure distributions of shock wave within hollow cylindrical NdFeB magnet caused by lateral impact of single-ended and double-ended initiating explosives, are dissected.

2. System model relations between demagnetization rate and shock wave pressure

The magnet's demagnetization rate reflects the demagnetization degree of a magnet under the action of shock wave. To explore the relations between demagnetization rate and shock wave pressure is of great significance to the design of explosively driven ferromagnetic seed source. A magnet's demagnetization rate can be expressed as the ratio of total flux variation to initial flux on a cross-sectional unit of the magnet, namely:

$$\eta^x = \frac{\Delta \Phi^x}{\Phi_0^x} \times 100\%$$  \hspace{1cm} (1)

The superscript $x$ represents a certain cross-sectional unit of the magnet. According to the law of electromagnetic induction, the variation in flux will bring about induced electromotive force within the coils around the cross-section:

$$E^x_s(t) = -\frac{d\Phi^x(t)}{dt}$$  \hspace{1cm} (2)

By calculating the integral of Eq. (2) within the time range of shock wave, we can get:

$$\Delta \Phi^x_j = -\int_0^{t_{sh}} E^x_s(t) \, dt$$  \hspace{1cm} (3)

where the variation in $E^x g(t)$ is acquired through experiments; the total flux variation $\Delta \Phi x f$ of the cross-section $x$ is the area formed by the waveform and time axis of induced electromotive force; the initial flux $\Phi x 0$ can be obtained through magnetostatic field computation of open-circuit magnet. Substitute $\Delta \Phi x f$ and $\Phi x 0$ into Eq. (1) to get the demagnetization rate of the cross-section $x$ under certain shock wave.

Figure 1. Schematic diagram of explosively driven ferromagnetic generator
Next, the calculation of shock wave pressure resulting from the shock wave on the cross-section $x$ is introduced. According to the momentum conservation expression during the impact loading process, we can get:

$$P_m = \rho_{m0} D_m u_m$$  \hspace{1cm} (4)

$P_m$ is the shove wave pressure of the magnet; $\rho_{m0}$ is the density of the magnet without impact; $D_m$ is the shove wave speed of the magnet; $u_m$ is the speed of particle in the magnet. The magnet's Hugoniot equation can be expressed as:

$$D_m = c_0 + \lambda u_m$$  \hspace{1cm} (5)

where $c_0$ and $\lambda$ are Hugoniot parameters of the magnet material; for pure iron material, $c_0 = 3.78$ km/s, $\lambda = 1.652$; for ferroalloy magnet, Hugoniot parameters can be obtained by adding up the volumes of mixtures or by data acquisition and linear fitting via comparative experimental method; $D_m$ can be obtained by calculating the electric pulse signal generated at the electric probes or parallel coils along the propagation direction of shock wave within the magnet. Assume that $\Delta L$ is the distance between two electric probes or coils; $t_{c1}$ and $t_{c2}$ are the moments when pulse signals are generated; then, the shove wave speed within the magnet can be expressed as:

$$D_m = \Delta L / (t_{c1} - t_{c2})$$  \hspace{1cm} (6)

After getting the values of $c_0$, $\lambda$ and $D_m$, in combination of Eq. (4) and (5), $P_m$ and $u_m$ can be obtained. In [8], for explosion products of explosives, Hugoniot equation can be expressed as:

$$P_0 = 2.412 P_{CJ} - \left(1.7315 \frac{P_{CJ}}{u_{CJ}}\right) u_m + \left(0.3195 \frac{P_{CJ}}{u_{CJ}}\right) u_m^2$$  \hspace{1cm} (7)

$P_0$ is the shock wave pressure of the contact surface between explosive and magnet; $P_{CJ}$ and $u_{CJ}$ are the pressure and particle speed of CJ (Chapman-Jouguet). By substituting the particle speed $u_m$ in Eq. (7), we can obtain $P_0$ value; the pressure range within the magnet under the loading of explosive shock wave is $P_m - P_0$. Sergey I. Shkuratov concluded that Nd$_2$Fe$_{14}$B rare earth permanent magnet is nearly fully demagnetized along the magnetization direction under the shock wave pressure of 28.2GPa-38.7GPa in [9]; Wu Junying et al. found that when the incident shock wave pressure of the magnet is 45GPa, 13.87GPa and 8.52GPa, the maximum demagnetization rate is 87.94%, 44.07% and 35.60%, respectively in [10].

3. Numerical simulation of demagnetization process under the loading of explosively driven shock wave

Whether the shock wave pressure in the magnet satisfies the demagnetization conditions of magnet is a precondition for the design of compact explosively driven ferromagnetic generator. A nonlinear finite element method (ANSYS/LS-DYNA) is adopted to conduct numerical simulation of impact loading process of the magnet and to analyze the propagating rules and pressure distribution of shock wave within the magnet.

The physical model is a hollow cylindrical magnet loaded with explosives with single-ended or double-ended initiating for lateral loading of shock wave. In the model, NdFeB is chosen as the material for the magnet, and Explosive 8701 is used. NULL model and Gruneisen state equation are used to describe the impact loading process of the magnet. In NULL model, deviatoric stress calculation can be avoided by calling state equation, and the lower limit of pressure is determined by cutoff pressure. NdFeB material has a density of 7.5g/cm$^3$ and an elasticity modulus of 160Gpa. The parameters of Gruneisen state equation can be obtained from Hugoniot curve data of NdFeB material. As shown in Table 1, $c_0$, $S_1$, $S_2$ and $S_3$ are the Hugoniot curve parameters of the magnet; $\gamma_0$ is Gruneisen coefficient; $a$ is the first-order volume correction of $\gamma_0$; $E_0$ is the internal energy density. Explosive 8701 has a density of 1.72g/cm$^3$, an explosive velocity of 8.43km/s and an explosive pressure of 30.56GPa. High-energy explosive model and JWL state equation are adopted. Table 2 presents the parameters of the state equation for explosive product JWL of Explosive 8701. The
The magnet in the model has an outer diameter of Φ50mm, an internal diameter of Φ15mm and a height of 30mm; the explosive has a diameter of Φ15mm and a height of 30mm.

| Table 1 | Parameters for Gruneisen state equation of NdFeB material [11] |
|---------|---------------------------------------------------------------|
|         | $c_0$ (cm/μs) | $S_1$ | $S_2$ | $S_3$ | $\gamma_0$ | $a$ | $E_0$(J/m$^3$) |
|         | 0.368         | 1.059 | 0     | 0     | 0.25        | 0.48 | 0            |

| Table 2 | Parameters for JML state equation of Explosive 8701 |
|---------|------------------------------------------------------|
|         | $A_1$(100GPa) | $A_2$(100GPa) | $R_1$ | $R_2$ | $\omega$ | $E_0$(J/m$^3$) |
|         | 8.802         | 0.174          | 4.600 | 1.200 | 0.300    | 0.104 |

3.1. Single-ended initiating

Figure 2 presents the isobaric lines of explosive and magnet at different moments when the single-ended initiating explosive applies load to hollow cylindrical NdFeB magnet. With the initiating moment of the explosive as the zero time, the detonation wave spreads downwardly as a spherical wave. At $t=0.89\mu$s, the spherical detonation wavefront reaches the contact surface of explosive and NdFeB, the shock wave enters NdFeB magnet, and the explosive continues to explode along the axial direction. At $t=2.01\mu$s, isobaric lines suggest that the detonation wave reaches the center section of NdFeB magnet, and it can be seen that the propagation speed of shock wave within NdFeB magnet is significantly slower than that of detonation wave. At this time, only about one fifth of the volume of the magnet is under impact. At $t=3.27\mu$s, the explosive wavefront has a maximum pressure value of 37.4GPa, and the explosive cylinder is nearly fully exploded, but the shock wave in the magnet still does not reach the side wall, and only about a half of the volume is under impact. At $t=3.67\mu$s, the explosive is fully exploded, and the detonation wavefront reaches the lower end, the shock wavefront in the magnet is significantly backward than detonation wavefront; next, the shock wave in the magnet continues to spread and reflect at the lower end. At $t=4.48\mu$s, the shock wave reaches the side wall of the magnet. It can be clearly seen that, there is a low pressure zone at the edge of the upper end of the magnet for single-ended initiating, and that this part of magnet cannot be demagnetized. In order to further analyze the variations in pressure, it is needed to monitor the variations in pressure of center section of NdFeB magnet at different heights.
Figure 2. Isobaric lines in the explosive and magnet for single-ended initiating at different moments

Fig. 3 delivers the pressure variation curve at different locations within NdFeB magnet in the case of single-ended initiating. In Fig. 3(a), at the center section of the magnet, the pressure variation curves at seven locations (with a radius of 7.5mm, 10mm, 15mm, 18mm, 21mm, 23mm and 25mm, respectively) along the radial direction are given. At $r=7.5$mm, the peak pressure reaches 36.2GPa; at $r=10$mm, the peak pressure quickly attenuates to about 19GPa; at $r=15$mm, 18mm, 21mm and 23mm, the peak pressure is 12.3GPa, 8.5GPa, 7.2GPa and 5.5GPa, respectively, and the attenuation degree of shock wave pressure gradually decreases. In Fig. 3(b), at the location with 1/2 radius to the magnet, the pressure variation curves at seven locations (at 0mm, 3mm, 5mm, 9mm, 11mm, 13mm and 15mm, respectively) along the depth direction are presented, and the peak shock wave pressures at these seven locations are 0.9GPa, 8.3GPa, 11.1GPa, 12.5GPa, 12.9GPa, 13.1GPa and 13.2GPa, respectively. Thus, it can be seen that the pressure increases slightly along the axial direction by following the propagation path of detonation wave, which also reflects the superiority of lateral impact over the longitudinal impact.

Figure 3. Pressure variation curves at different locations within the magnet in the case of single-ended initiating

3.2. Double-ended initiating

Figure 4 presents the isobaric lines of explosive and magnet at different moments when the double-ended initiating explosive applies load to hollow cylindrical NdFeB magnet. With the initiating moment of the explosive as the zero time, the detonation waves spread from two ends to the center as two spherical waves. At $t=0.96\mu$s, the spherical detonation wavefronts reach the contact surface of
explosive and NdFeB, and the shock waves enter NdFeB magnet. At $t=1.74\mu s$, the two spherical waves meet at the center of the explosive, and the detonation waves overlay and enhance each other; at $t=2.32\mu s$, the overlapped shock waves in the magnet have a lateral impact on NdFeB magnet; at $t=4.18\mu s$, the shock wave reaches the edge of the magnet. It takes about $3.22\mu s$ for the shock wave to fully penetrate through the magnet from entering the magnet. Since the two shock waves overlay at the center, the pressure value at the center is high, while the pressures at both ends are low. Yet, the shock wave pressures at the edge for double-ended initiating are significantly higher than those at the edge for single-ended initiating, and all magnet experiences the process of demagnetization.

**Figure 4.** Isobaric lines in the explosive and magnet for double-ended initiating at different moments

In order to further analyze the variations in pressure, it is needed to monitor the variations in pressure of center section of NdFeB magnet at different heights. Fig.5 presents the pressure variation curve at different locations within NdFeB magnet in the case of double-ended initiating.
Figure 5. Pressure variation curves at different locations within the magnet in the case of double-ended initiating

In Figure 5 (a), at the center section of the magnet, the pressure variation curves at five locations (with a radius of 7.5mm, 12mm, 17mm, 20mm and 25mm, respectively) along the radial direction are given. At $r=7.5\text{mm}$, the peak pressure reaches up to 60.90GPa, far exceeding the critical demagnetizing pressure of the magnet; at $r=12\text{mm}$, the peak pressure rapidly attenuates to 27.62GPa; at $r=17\text{mm}$ and $r=20\text{mm}$, the peak pressures are 18.5GPa and 14.8GPa, respectively, and the attenuation degree of shock wave pressure gradually decreases. In Figure 5 (b), at the location with 1/2 radius to the magnet, the pressure variation curves at five locations (at 3mm, 5mm, 9mm, 11mm and 15mm, respectively) along the depth direction are presented, and the peak shock wave pressures at these five locations are 5.9GPa, 8.5GPa, 12.8GPa, 17.3GPa and 26.5GPa, respectively.

4. Conclusions

According to the theoretical analysis and numerical simulation results, it can be concluded that when the single-ended initiating explosive has a lateral impact on hollow cylindrical magnet, there is a low-pressure zone at the edge of the initiating end, and this part of magnet cannot be demagnetized; there is a huge difference in the propagation speeds of shock wave and denotation wave in NdFeB magnet; when the impact wave enters NdFeB magnet, the pressure will soon attenuate; with the increase of propagation distance, the attenuation degree of the pressure gradually decreases; the center section of the magnet has the most flux where the incident shock wave pressure basically meets the demagnetization requirements. When the double-ended initiating explosive has a lateral impact on hollow cylindrical magnet, since the shock waves overlay at the center, the pressure at the magnet center is very high, while the pressures at both ends are low; double-ended initiating has faster demagnetization rate, swifter variation in flux and higher induced electromotive force compared to single-ended initiating; the incident shock wave pressure at the center section of the magnet reaches more than 60GPa, far exceeding the critical demagnetization pressure of the magnet.

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