Study on the functional rule of exploding foil multi-point synchronous explosive

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Abstract. In order to study the effect of series initiation and parallel initiation on multi-point synchronous initiation of EFI (Exploding Foil Initiator, EFI), two-point series and two-point parallel electric explosion, three-point series and three-point parallel electric explosion of exploding foil were tested in this paper. The electrical explosion parameters for synchronous initiation of exploding foil two-point in series and two-point in parallel were tested also. The electric explosion parameters of exploding foil varies with the initiation voltage were analyzed. The effects of series initiation and parallel initiation on the performance of exploding foil multi-point synchronous initiation were obtained. The initiation sensitivity test of three-point series EFI and four-point hybrid EFI was carried out. The experimental results agree well with the analysis law. The research results show that series initiation is beneficial to improve the consistency of initiation conditions at each point on the condition of exploding foil multi-point initiation, is beneficial to improve the synchronization of multi-point initiation. But it’s adverse to the full release of system energy when the number of series initiation points is large. Parallel initiation is beneficial to improve the system energy utilization. But the explosion synchronization relatively poor when system energy is low. The explosion synchronization of exploding foil will be better when system energy increase. It’s benefits to increase the consistency of initiation conditions at each point of exploding foil, benefit to increase the system energy utilization and reduce system firing energy that adopt reasonable combination of series and parallel, when the number of initiation point is large and system energy is sufficient.

1. Introduction
As we know, there is no primary explosive in the EFI (Exploding Foil Initiator, EFI), the detonator charge, HNS-IV explosive is directly detonated by the flyer. Compared with the traditional detonator, EFI has higher safety, a shorter action time and a higher action synchronicity when multiple synchronous initiation occurs. In view of the safety advantage of exploding foil initiation technology and the high synchronization of multi-point initiation of EFI, the multi-point synchronous initiation device of EFI has a good application prospect in the military [1-6].

In this paper, the explosion parameters of two-point series, two-point parallel and three-point series, three-point parallel initiation of bridge foil are compared, such as explosion
current, explosion voltage and synchronization time. The explosion parameters of two-point series, two-point parallel four-point synchronous initiation of bridge foil are tested. Based on the analysis of the electric explosion parameters of the bridge foil with the change of the initiation voltage, the influence of series initiation and parallel initiation on the multi-point synchronous initiation performance of the exploding foil is obtained. The research results have reference significance for improving the energy utilization rate of the system, the synchronism and the reliability of multi-point synchronous initiation.

2. Test equipment and test methods

2.1. Test equipment
The equipment used in the test mainly includes high-voltage power supply, digital high-voltage meter, pulse power source, oscilloscope, Rogowski coil, voltage divider, etc. Among them, the firing capacity of the pulse power source is 0.22 μ F, withstand voltage is 4kV; the attenuation times of the burst current and burst voltage signals collected by Rogowski coil and voltage divider are 100 times.

2.2. Sample
Single point exploding foil, bridge area size 0.4m m × 0.4mm, copper foil thickness 4 μ m; two-point exploding foil in series, bridge area size 0.4mm × 0.4mm, copper foil thickness 4 μ m, the center of the bridge area is 10 mm apart; three-point exploding foil in series, bridge area size 0.4mm × 0.4mm, copper foil thickness 4 μ m, the center of the bridge area is 10 mm apart.

2.3. Test methods
The high-voltage power supply provides the charging power and trigger signal for the pulse power source. The digital high-voltage meter is used to monitor the charging voltage of the pulse power source. The Rogowski coil is used to collect the current signal of the exploding foil circuit. The voltage signal of the two ends of the bridge is collected by the voltage divider. The collected signal is recorded by the oscilloscope. When initiating in parallel, it is necessary to test the discharge performance of each discharge branch, so that the inductance value of each discharge branch is basically the same. The initial test point of EFI is set as 1.5kV, with 500V as the step, to 3.5kV. The highest point of the voltage curve is the explosion point of the bridge foil, the corresponding voltage value is the explosion voltage, the corresponding time is the explosion time, and the corresponding current value of the current curve is the explosion current; when multiple bridge foils are detonated synchronously, the explosion time difference of the bridge foil is the multi-point explosion synchronous range. The typical three-point series exploding foil current and voltage test curve is shown in figure 1.
3. Test results and analysis

3.1. Comparison of explosion performance of bridge foil with two-point series connection and two-point parallel connection

The test results of the bridge foil explosion parameters in two-point series are shown in table 1.

| Resistance / mΩ | Charging voltage / kV | Explosion voltage / V | Explosion current / A | Explosion time / ns | Current peak time / ns |
|-----------------|-----------------------|-----------------------|-----------------------|---------------------|-----------------------|
| 45              | 1.5                   | 980                   | 500                   | 333                 | 216                   |
| 46              | 900                   | 480                   | 330                   |                     |                       |
| 48              | 2.0                   | 1260                  | 860                   | 232                 | 192                   |
| 46              | 1320                  | 860                   | 240                   |                     |                       |
| 42              | 2.5                   | 1520                  | 1280                  | 210                 | 165                   |
| 46              | 1480                  | 1240                  | 206                   |                     |                       |
| 57              | 3.0                   | 1720                  | 1560                  | 176                 | 146                   |
| 58              | 1620                  | 1600                  | 184                   |                     |                       |
| 58              | 3.5                   | 2000                  | 2220                  | 152                 | 235                   |
| 60              | 1760                  | 2240                  | 154                   |                     |                       |

The test results of electrical explosion parameters of bridge foil in two-point parallel are shown in table 2.

| Resistance / mΩ | Charging voltage / kV | Explosion voltage / V | Explosion current / A | Explosion time / ns | Current peak time / ns |
|-----------------|-----------------------|-----------------------|-----------------------|---------------------|-----------------------|
| 46              | 1.5                   | Exploions of bridge foils are incomplete, signals not captured. |                     |                     |                       |
| 46              | 2.0                   | 760                   | 380                   | 321                 | 189                   |
| 46              | 340                   | 260                   | 387                   | 179                 |                       |
| 47              | 2.5                   | 1120                  | 880                   | 270                 | 170                   |
| 46              | 1040                  | 840                   | 249                   | 162                 |                       |
| 45              | 3.0                   | 1400                  | 1480                  | 220                 | 165                   |
| 46              | 1440                  | 1600                  | 214                   | 160                 |                       |
| 48              | 3.5                   | 1280                  | 2000                  | 189                 | 166                   |
| 44              | 1680                  | 1920                  | 182                   | 154                 |                       |

Chart the test data. The two bridge foils are named bridge foil A and bridge foil B. Compare the burst current and burst time under different charging voltage. The results are shown in figure 2 and figure 3.
Figure 2. Electrical explosion performance of two-point series exploding foil.

Figure 3. Electrical explosion performance of two-point parallel exploding foil.

It can be seen from the comparison of test data and charts that, for two-point series bridge foils, the explosion current of two bridge foils has a high consistency; the explosion synchronization of two bridge foils is better. The synchronization of two bridge foils under different firing voltage is within 10ns. When the two-point series bridge foil is detonated, the pulse power source discharge has only one circuit, and the connection mode of the two-point series bridge foil is voltage sharing. The test results show that the explosion current of the two-point series bridge foil under each ignition voltage is very close (difference $\leq 4\%$). The bridge foil series connection ensures the consistency of the initiation conditions of the bridge foil to the greatest extent, which shows that the series initiation can improve the synchronization of the multi-point explosion of the bridge foil.

For the two-point parallel bridge foil, the pulse power source has two discharge branches, which share the discharge current of the pulse power source to realize the initiation. It can be seen from the test results that when the charging voltage of the pulse power source is 1500V, the initiation of the bridge foil is not complete. It shows that the current shunting has a great influence on the explosion performance of the bridge foil when the energy supply of the system is low. When the charging voltage is low, the burst current consistency and burst synchronization of the bridge foil initiation in parallel mode are not as good as that in series mode. With the increase of charging voltage, the synchronicity of bridge foil explosion increases gradually, which shows that the synchronicity of bridge foil parallel initiation increases gradually when the energy supply of bridge foil initiation is sufficient.
3.2. Comparison of three-point series and three-point parallel electrical explosion performance of bridge foil

The test results of the parameters of the bridge foil electrical explosion in three-point series are shown in table 3.

| Resistance / mΩ | Charging voltage / kV | Explosion voltage / V | Explosion current / A | Explosion time / ns | Current peak time / ns |
|-----------------|----------------------|-----------------------|-----------------------|---------------------|-----------------------|
| 46              | 1.5                  | 1160                  | 240                   | 234                 | 163.2                 |
| 46              | 2.0                  | 1160                  | 740                   | 222                 | 155                   |
| 47              | 2.5                  | 1160                  | 222                   |                     |                       |
| 45              | 3.0                  | 1620                  | 1300                  | 187                 | 134                   |
| 48              | 3.5                  | 1400                  | 1660                  | 166                 | 127                   |

Explosions of bridge foils are incomplete, signals not captured.

The test results of the parameters of the bridge foil electrical explosion under the condition of three-point parallel connection are shown in table 4.

| Resistance / mΩ | Charging voltage / kV | Explosion voltage / V | Explosion current / A | Explosion time / ns | Current peak time / ns |
|-----------------|----------------------|-----------------------|-----------------------|---------------------|-----------------------|
| 48              | 1.5                  | 1160                  | 240                   | 234                 | 163.2                 |
| 46              | 2.0                  | 1160                  | 740                   | 222                 | 155                   |
| 45              | 2.5                  | 1160                  | 222                   |                     |                       |
| 55              | 3.0                  | 1400                  | 1660                  | 166                 | 127                   |
| 48              | 3.5                  | 1420                  | 1660                  | 219                 |                       |
| 46              | 3.5                  | 820                   | 1520                  | 204                 | 145                   |
| 57              | 1240                 | 1080                  | 228                   |                     |                       |

Explosions of bridge foils are incomplete, signals not captured.

Because the three-point parallel bridge foils completely explodes only at 3.5kV and the test data is less, only the three-point series bridge foil electric explosion test data are processed graphically. The three bridge foils are named bridge foil A, bridge foil B and bridge foil C respectively, and their burst times under different charging voltages are compared. The results are shown in figure 4.
Figure 4. Electrical explosion performance of three-point series exploding foil.

It can be seen from the test data and charts of three-point series synchronous initiation of bridge foil that the three-point series bridge foil cannot fully explode when the charging voltage of pulse power source is 1.5kV, which indicates that the three-point series initiation of bridge foil requires high initiation energy. Compared with the two-point series initiation, the three-point series bridge foil initiation synchronization is slightly worse, which is less than 20 ns, indicating that with the increase of the number of initiation points, the synchronous of multi-point bridge foil initiation decreases.

Due to there are three parallel discharge branches, the shunt effect of each branch is more obvious when the three-point parallel initiation of the bridge foil is carried out. With the increase of the number of initiation points and the enhancement of the shunting effect, it is more difficult to achieve the initiation conditions of the bridge foil. Under the five ignition voltages of the pulse power source, only 3.5kV charging voltage makes the bridge foils fully explode. Under other conditions, the bridge foils cannot fully explode, and the effective signal cannot be captured.

3.3. Electrical explosion test of four-point hybrid bridge foil

The explosive foil four-point array adopts two-point in series and two-point in parallel. Limited by the test conditions, it is difficult to collect all the parameters of the four-point bridge foil electric explosion separately. Because the explosion synchronization and the consistency of the explosion current are high when two points are connected in series, one point is selected from the corresponding position of the two parallel branches for data collection, which represents the parameters of the bridge foil electrical explosion of the branch. The test data is shown in table 5.

Table 5. Electrical explosion parameters of two-point in series and two-point in parallel exploding foil.

| Resistance / mΩ | Charging voltage /kV | Explosion voltage /V | Explosion current /A | Explosion time /ns | Current peak time /ns |
|----------------|----------------------|----------------------|----------------------|-------------------|----------------------|
| 33             | 1.5                  | Explosions of bridge foils are incomplete, signals not captured. |
| 32             | 2.5                  | Explosions of bridge foils are incomplete, signals not captured. |
| 32             | 3.0                  | 900                  | 1160                 | 264               | 174                  |
| 33             | 3.0                  | 980                  | 1160                 | 255               | 170                  |
It can be seen from the test data that, due to the lack of energy supply of the system, when the charging voltage of the pulse power source is 2.5kV, the bridge foil explosion is incomplete and no effective signal is captured. The explosion synchronization of the two parallel branches is high, which is within 10ns. Compared with the experimental results of three-point series connection, it can be found that when the charging voltage of pulse power source is 3.5kV, the explosion current of two series two parallel four-point bridge foil reaches the level of three-point series bridge foil explosion current under the same voltage, which shows that the explosion of four-point bridge foil (two series and two parallel) has higher energy utilization.

3.4. Verification test of EFI multi-point synchronous firing sensitivity

3.4.1. EFI three-point series ignition sensitivity test. The Langley method is adopted in the test, and the lower limit of initiation voltage is 1800V and the upper limit is 2800V. When all three ignition points are ignited, it is considered that they can ignite, which is recorded as "1"; if any one of the three points is not ignited, it is considered that the array fails to ignite, which is recorded as "0". The firing capacity of the pulse power source is 0.4μF. The test results are shown in table 6.

| Serial number | Resistance /mΩ | Charging voltage /V | Ignition |
|---------------|----------------|---------------------|----------|
| 1             | 123.8          | 2300                | 1        |
| 2             | 127.6          | 2050                | 1        |
| 3             | 132            | 1925                | 1        |
| 4             | 120            | 1862.5              | 0        |
| 5             | 118            | 1894                | 0        |
| 6             | 129            | 1972                | 0        |
| 7             | 125            | 2136                | 1        |
| 8             | 125            | 2053                | 1        |
| 9             | 133            | 1973                | 0        |

According to the test results, the ignition point of EFI three-point serial connection is calculated, and 50% ignition (mean value) voltage is 1976V; 99% ignition (full firing) voltage is 2176V; 0.1% ignition (non firing) voltage is 1775V; variance (uncertainty) is 64.8V. The critical ignition energy is about 0.86j and the total ignition energy is about 1.04J.

3.4.2. EFI initiation sensitivity test of four-point hybrid. The explosive foil four-point array adopts two points in series and two points in parallel. The Langley method is adopted in the test, and the lower and upper limit of initiation voltage are 1700V and 2700V respectively. When all four-point arrays are detonated, it is considered that they can ignite, which is recorded as "1"; if any one of the four points is not ignited, it is considered that the array fails to ignite, which is recorded as "0". The firing capacity of the pulse power source is 0.4μF. The test results are shown in table 7.
Table 7. Test results of EFI initiation sensitivity test of four-point hybrid.

| Serial number | Resistance / mΩ | Charging voltage / V | Ignition |
|---------------|-----------------|----------------------|----------|
| 1             | 47              | 2200                 | 1        |
| 2             | 42              | 1950                 | 1        |
| 3             | 45              | 1825                 | 0        |
| 4             | 41              | 1887                 | 0        |
| 5             | 47              | 2043                 | 1        |
| 6             | 44              | 1965                 | 0        |
| 7             | 45              | 2005                 | 1        |
| 8             | 49              | 1985                 | 0        |
| 9             | 44              | 1995                 | 1        |
| 10            | 47              | 1990                 | 0        |
| 11            | 45              | 1992                 | 1        |

According to the test results, the firing point of EFI four-point array is calculated, and the 50% firing (mean value) voltage is 1973V; 99% firing (full firing) voltage is 2114V; 0.1% firing (non firing) voltage is 1832.5V; variance (uncertainty) is 45.6V. The critical ignition energy is about 0.856J and the total ignition energy is about 0.98J.

It can be seen from the comparison test of the initiation sensitivity of EFI three-point series initiation array and EFI four-point (two-point series and two-point parallel, four point hybrid mode) initiation array that under the same firing energy, the initiation sensitivity of the four-point initiation array is even slightly better than that of the three-point series initiation array, which indicates that when there are many firing points and the system energy supply is sufficient, appropriate series parallel hybrid mode should be adopted. The joint mode is conducive to the full release of the energy of the pulse power source, which can improve the energy utilization rate of the system and reduce the initiation energy of the system.

4. Conclusion
Through the comparative test of two-point series and two-point parallel electric explosion performance of bridge foil, the comparative test of three-point series and three-point parallel electric explosion performance, and the test results of four-point synchronous initiation electric explosion performance of two-point series and two-point parallel of bridge foil, the following conclusions can be obtained through comparative analysis:

(1) The series initiation can improve the consistency of the initiation conditions of the bridge foil and the synchronization of the multi-point initiation. However, with the increase of the number of series connection points, the dynamic resistance increases when the bridge foil is detonated, which is not conducive to the full release of the pulse power source energy.

(2) When the energy supply is low, the parallel initiation of bridge foil is greatly affected by the current shunt effect, and the synchronization of bridge foil explosion is relatively poor compared with the series initiation. When the energy supply of bridge foil initiation is sufficient, the synchronization of bridge foil parallel initiation is gradually improved.

(3) When the number of initiating points is large and the energy supply of the system is sufficient, the appropriate series parallel hybrid mode is benefits to the full release of the pulse power source energy, which can improve the energy utilization rate of the system and reduce the system ignition energy.
References

[1] Col Scott Flynn 2008 ARDEC Overview Int. 52th Annual Fuze Conference. (Sparks, NV)

[2] Gene Henderson 2008 AMRDEC Overview Int. 52th Annual Fuze Conference. (Sparks, NV)

[3] Col Scott Flynn 2009 ARDEC Overview Int. 53th Annual Fuze Conference. (Lake Buena Vista, FL)

[4] Yang Zhen-ying, Ma Si-xiao and Chu En-yi etc 2001 Study on the Exploding Foil Multi-point Initiation Device Initiators & Pyrotechnics 4 9-11

[5] Qin Guo-sheng, Zhang Rui and Wang Yin etc 2016 Numerical Simulation and Experimental Study of Multi-point Array EFI Acta Armamentarii s2 81-85

[6] Liang Che-ping, Zhang Yu-ruo and Jin Li etc Research on a Multi-point Simultaneous Initiation System Based on EFI Explosive Materials 47(03) 31-36