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Fireset

Ronald S. Lee

February 19, 1988

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FIRESET

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Introduction

FIRESET is a PC-based computer code which calculates current as a function of time for an RLC circuit containing up to fifteen series conductors which undergo rapid heating and subsequent explosion as a consequence of an electric current which passes through them. In its original form, the code was developed to model electrical waveforms measured when a large, typically 25.4 x 25.4 x 0.051-mm, aluminum foil was exploded using a capacitor bank with tens of kilojoules of stored energy. The code proved to be useful for this purpose, and it was recognized that it could also be used for modeling the electrical response of detonator bridgewires.

In view of the increasing use of slapper detonators for DOD applications, we wish to make the latest version of the code, available to DOD laboratories and contractors for use in designing firing systems which employ slapper or exploding bridgewire detonators.

The code prompts the user to supply the necessary input data and, as it solves the differential equations, it displays a plot of current vs time on the monitor screen. A hard copy of the plot may be obtained by pressing the "shift" and "print screen" keys at the same time. Burst time and burst current are printed out for each bridge conductor and, if desired, the printer will print out values of time, current, di/dt , average specific action through the bridges, and total voltage across the bridges after every five time steps. The capability for handling up to fifteen bridges in series is useful for applications involving multiple initiation points or for simulating a circuit with a single, contoured bridge.

The circuit equations are solved numerically using a fourth-order Runge-Kutta method with Gill's modification. The user may select the maximum error per time step and, if the chosen time step is too large, the code will automatically adjust the time step to stay within the chosen error per step. It is difficult to estimate the cumulative error, however, so a problem should be run with more than one time step to make sure the solution is accurate.

The BASIC program implementing this calculation was taken from Numerical Methods for the Personal Computer, Terry E. Shoup, Prentice Hall, Englewood Cliffs, N.J., 1984. The program has been compiled using Microsoft's BASIC compiler. FIRESET will run on most IBM PCs and clones. The difficulties I have encountered in running on non-IBM equipment have involved the graphics board. Graphics boards which do not emulate the IBM graphics board may not run the code. In particular, I have encountered difficulty with Hercules boards.

Modeling Electrically Exploded Conductors

The heart of the FIRESET code is a model for the resistivity of the bridge conductor as it heats up and explodes. A detailed, physically realistic model of the resistivity of an electrically exploded conductor presents many difficulties. These difficulties can be circumvented by using an empirical model which is derived from experimental data. Such a model must be used with caution outside of the range of the data to which it is normalized precisely because it does not include the details of the physics, but within this range and for modest extrapolations, it can be extremely useful as a design tool.

If one measures the current and voltage across a conductor as it is electrically exploded, one finds that the resistance increases quite slowly until the time when the conductor explodes (burst), where it exhibits a sharp peak. After burst, the resistance settles down to a new, higher value which is slowly decreasing with time. Four parameters are used to describe the dynamic resistance of the conductor: a parameter which describes where burst occurs on the current waveform, peak resistivity at burst, the width of the resistivity peak, and the resistivity after burst (assumed constant). The original dimensions of the bridge conductor are used to compute resistance from the resistivity parameters.

The most useful progress variable to describe the course of an electrical explosion is the specific action, $g(t)$, through the conductor, defined as

$$g = \int_0^t j^2(t) dt \quad (1)$$

where $j(t)$ is current density and t is time. If we neglect the expansion of the conductor during the explosion, specific action is independent of the conductor geometry. Specific action is a more convenient variable to use than energy density because it can be easily measured and it does not require knowledge of the thermodynamic state of the conductor for its calculation.

In the FIRESET model the dynamic resistance of an exploding conductor is defined as $R[g(t)]$, where time is an implicit variable. It has been found experimentally [Anderson and Nielson, 1959] that specific action to burst, g_0 , is approximately con-

stant, independent of the conductor cross-section and current waveform. If $j(t)$ can be calculated, one can predict the burst time from the equation

$$g_b = \int_0^{t_b} j^2(t) dt \quad (2)$$

where t_b is the burst time relative to the time of current start. In the FIRESET model, specific action to burst is the parameter which determines where burst occurs on the current waveform.

The mathematical form of $R(g)$ was determined from consideration of experimental data. An example of an experimentally determined $R(g)$ curve is shown in Figure 1, which shows resistivity as a function of specific action for a 9.53-mm-square, 0.052-mm-thick aluminum foil which was exploded using a capacitor bank. Current and voltage across the foil were measured and digitized. Resistivity and specific action were calculated assuming that the dimensions of the foil did not change during the explosion.

Figure 1. Resistivity vs specific action for a 9.53 x 9.53 x 0.052-mm-thick aluminum foil. The squares are determined from experimental data and the solid line is from the FIRESET model.

In initial modeling attempts the experimental curve was used to calculate the current in a RLC circuit containing an exploding conductor. Circuit current was calculated from the equation

$$-\frac{Q}{C} + iR + L \frac{di}{dt} = 0 \quad (3)$$

subject to the initial condition $Q(0)=CV_0$, $(di/dt)_0=V_0/L$, where C , L , and V_0 are respectively the system capacitance, inductance and initial charging voltage. The resistance R is the sum of a fixed system resistance, R_0 , and the dynamic resistance, $R(g)$. Using the empirical relation shown in Figure 1 and experimental values of C , L , and V_0 , one can numerically integrate Eq. 3 to determine $i(t)$.

It proved to be impossible to reproduce the experimental waveforms over any appreciable range of charging voltages by using a single $R=R(g)$ relationship, so an analytical relationship was devised which approximated the shape of the experimental $R(g)$ curve, but which could be further adjusted to fit experimental waveforms over a wider range of charging voltages.

The general features of the experimental $R(g)$ curves are a resistivity peak and a higher, nearly constant resistivity after burst. A Gaussian function was chosen to model the resistivity peak because the peak position and width can be easily and independently varied. Initial heating and post-burst resistivity were modeled by a function which was chosen so that it varied smoothly from zero up to a constant value. The final expression for resistivity is given by

$$\rho(g) = A \left[1 - \text{sech} \left(\frac{g}{g_0} \right) \right] + B \exp \left[\left(- \frac{g-g_0}{s} \right)^2 \right] \quad (4)$$

where the four model parameters are A , the post-burst resistivity, B , the height of the resistivity peak, S , the width of the resistivity peak and g_0 , the specific action to burst. One sees that the use of the Gaussian function ensures that the resistivity peak will occur at $g=g_0$.

Further refinement was necessary before the model could successfully predict current waveforms over a wide range of experimental parameters. We observe experimentally that specific action to burst is only approximately constant. We have accumulated data on electrically exploded foils over a wide range of

capacitor discharge systems and conductor geometries. Figure 2 shows a log-log plot of specific action vs the initial rate of current rise from the capacitor bank, V_0/L . The data span over two orders of magnitude in V_0/L and are mostly from experiments where large capacitor banks were used to explode aluminum foils of enormous cross section relative to the dimensions of slapper detonators. Dimensions of the square bridgefoils varied from 1-38 mm, with thicknesses in the range 0.025-0.15 mm. Bank charging voltages ranged from 10-100 kV.

The data of Figure 2 suggest that a power-law scaling of the form

$$g_0 = G_0 (V_0/KL)^P \quad (5)$$

would be an appropriate way to scale specific action to bursts for capacitor discharge systems with differing rates of current rise. The straight line in Figure 2 is from Eq. (5) with $K = 2(10^{11})\text{A/s}$ and $P = 0.19$. This value of P is probably not the optimum, but it gives good agreement with experimental data for both aluminum and copper conductors and the calculational results are not very sensitive to the choice of P . The increase of g_0 at higher discharge rates may be due to confinement of the conductor by its own inertia and inertia of surrounding material.

In the FIRESET model we thus scale g_0 according to Eq. (5) and S according to

$$S = S_0 (V_0/KL)^P, \quad (6)$$

where $K = 2(10^{11})\text{A/s}$ and $P = 0.19$.

Model parameters for aluminum which give a good representation of burst times and burst currents over a wide range of data are

$$\begin{aligned} A &= 90 \text{ Ohm-cm} \\ B &= 140 \text{ Ohm-cm} \\ G_0 &= 9(10^8) \text{ A}^2\text{-s/cm}^4 \\ S_0 &= 1.8(10^8) \text{ A}^2\text{-s/cm}^4. \end{aligned}$$

Model parameters for copper are

$$\begin{aligned} A &= 100 \text{ Ohm-cm} \\ B &= 200 \text{ Ohm-cm} \\ G_0 &= 2.5(10^9) \text{ A}^2\text{-s/cm}^4 \\ S_0 &= 2.5(10^8) \text{ A}^2\text{-s/cm}^4. \end{aligned}$$

Our experience has been that the code does a good job of simulating current waveforms for bridges fired on the same system, but that the parameters may need adjusting for use on a firing system with much different characteristics. For example, the code was originally normalized to data from large capacitor banks, and to correctly model the waveforms for detonator-sized aluminum bridgewires, it was necessary to use a value of $2(10^9)$ $A^2\text{-s/cm}^4$ for G_0 . The default model parameters in the code are for copper bridgefoils. It is easy to change the model parameters in the code if the default parameters do not give a good representation of the experimental waveforms.

Figure 2. Specific action vs initial di/dt. The squares are experimental data. The straight line represents the scaling law for g_0 used in the model.

Running the FIRESET code

I will give explicit instructions, in case the user is not familiar with the IBM PC.

1. Insert the FIRESET diskette in drive A, close the drive door and turn on the computer. Also turn on the monitor and printer, if they are not plugged into the same outlet box. If the printer is not on line, the computer will respond with a "device timeout" error when the computer tries to send data to the printer.
2. The code is compiled using the Microsoft BASIC compiler and expects to see an IBM graphics board. If the code does not work with your non-IBM graphics board, you may be able to run it by recompiling the BASIC source code with a compiler that is compatible with your graphics board.
3. An autoexec.bat file will automatically load FIRESET and a PC utility file, GRAPHICS. The GRAPHICS file allows you to generate a copy of the on-screen graphics by simultaneously pressing the "shift" and "print screen" keys. At this point, the following message will be displayed on the screen.

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This code calculates time, current and voltage at burst time for a RLC circuit coupled to up to 15 bridgewires in series. The user must specify the initial time step, system inductance, capacitance, charging voltage and system resistance, as well as the length, width and thickness of each bridgewire

The resistivity model is an empirical function, normalized to data from large capacitor banks exploding large foils. The resistivity is given by

$$RHD = A * (1 - \text{sech}(g/g_0)) + B * \exp\{-[(g-g_0)/S]^2\},$$

where $g_0 = G_0 * (V_0/L)^{0.19}$ and $S = S_0 * (V_0/L)^{0.19}$.

Specific action to burst is denoted by g . The user can choose other values of A, B, G_0 and S , if desired. It is also sometimes necessary to change the value of the error allowed by the code at each time step, if the code is choosing time steps that are too small.

To continue, press any key.

To abort during execution of program, press any key.

4. Now press any key to begin entry of the input data. Your first entry is the time step size. The size you choose depends on the duration of the record you want to simulate and the accuracy desired in the calculation. For a quick survey of records lasting several microseconds, a time step of 10 or 20 ns might be satisfactory. For a careful calculation of a record that lasts 500 ns, I would probably use a time step of 0.5 ns or less. If the time step is chosen too large, the code will adjust the time step to keep the error per time step within the bounds you have chosen, but when accuracy is desired, one should make sure the solution has converged by running the problem with successively smaller time steps.

5. FIRESET will prompt you for the values of system inductance, capacitance, charging voltage, resistance, number of bridgewires and bridgewire lengths and widths. If you make a mistake in entering the data, ignore it because you will be able to correct it later. The printer will echo all of your entries, so you can verify the values you have entered before you run the code. The screen display up to this point is shown below.

```
INPUT STEP SIZE IN NS
? 1
INPUT SYSTEM INDUCTANCE IN NANOHENRYS
? 90
INPUT CAPACITANCE IN MICROFARADS
? .5
INPUT CHARGING VOLTAGE IN KILOVOLTS
? 5
INPUT SYSTEM RESISTANCE IN MILLIOHMS
? 75
INPUT NUMBER OF BRIDGEWIRES (1-15)
? 1
INPUT BRIDGEWIRE DIMENSIONS IN INCHES
ENTER LENGTH, WIDTH, THICKNESS FOR BW1 1
? .02,.02,.000175
```

6. The next prompts are concerned with data I/O. The program asks whether printer output is desired. If the answer is yes, the values of time, current, (dI/dt) , specific action through the bridge and voltage across the bridges are printed out at every fifth time step. Usually the graphical output is sufficient, but the print option is available if desired. The next question is the time at which the computation should stop. The user must also specify the maximum current expected. The screen messages are displayed below.

```
PRINTER OUTPUT?  Y/N
? n
INPUT MAX TIME IN MICROSECONDS
? 1
INPUT MAX CURRENT IN KILOAMPERES
? 10
DO YOU WANT TO CHANGE DEFAULT RESISTIVITY PARAMETERS?  Y/N
?
```

The next prompt allows the user to change the default resistivity parameters. Let us suppose that the bridgefoil for which we have entered the dimensions is aluminum instead of copper. Then we would answer yes to the prompt and would be asked to supply the four model parameters for computing the resistivity of the foil. If we press "enter", the default value will be used, otherwise the value we enter is used in the calculation. The next-to-last prompt, which asks for the error per step can usually be ignored. On rare occasions it is possible to specify a problem which will run very slowly if the error per step is not increased, but this is unlikely. The last prompt asks whether any input parameters should be changed. Let us assume that the input parameters are all correct and that we press "enter". The prompts and responses are displayed below.

DO YOU WANT TO CHANGE DEFAULT RESISTIVITY PARAMETERS? Y/N
 ? y
 INPUT BURST PARAMETERS. FOR CU DEFAULT VALUES PRESS RETURN
 INPUT A IN MICROOHM-CM (DEFAULT IS A=100)
 ? 90
 INPUT B IN MICROOHM-CM (DEFAULT IS B=200)
 ? 140
 INPUT G0 IN A²-S/CM⁴*1E9 (DEFAULT IS 2.5)
 ? .89
 INPUT S IN A²-S/CM⁴ (DEFAULT IS 0.5)
 ? .18
 INPUT ERROR PER STEP (DEFAULT IS EPS=0.1)
 ?
 DO YOU WANT TO CHANGE ANY INPUT PARAMETERS? Y/N
 ? n

As the responses are entered, the printer will record the values of the selected input parameters. I usually cut these out and paste them onto the hard copy of the graphical output, as will be shown below. Since printer output was selected, the printer will print as the calculation proceeds and the printer output is shown below. The burst time and burst current are always printed, regardless of whether the print option has been selected. The print option output is shown below.

TIME	I	IDOT	ACTION	V
0.300000E-08	0.166453E+03	0.554113E+11	0.543745E+05	0.126992E-08
0.800000E-08	0.442861E+03	0.551471E+11	0.102764E+07	0.384618E-03
0.130000E-07	0.717875E+03	0.548533E+11	0.439381E+07	0.115400E-01
0.180000E-07	0.991345E+03	0.545299E+11	0.116192E+08	0.111277E+00
0.230000E-07	0.126312E+04	0.541736E+11	0.241430E+08	0.611187E+00
0.280000E-07	0.153302E+04	0.537815E+11	0.433741E+08	0.238359E+01
0.330000E-07	0.180079E+04	0.533218E+11	0.706859E+08	0.735826E+01
0.380000E-07	0.206608E+04	0.527988E+11	0.107409E+09	0.190725E+02
0.430000E-07	0.232825E+04	0.520727E+11	0.154817E+09	0.428918E+02
0.479999E-07	0.258645E+04	0.512435E+11	0.214105E+09	0.852080E+02
0.529999E-07	0.283929E+04	0.499535E+11	0.286354E+09	0.151174E+03
0.579999E-07	0.308548E+04	0.486221E+11	0.372495E+09	0.245374E+03
0.629999E-07	0.332243E+04	0.461770E+11	0.473264E+09	0.431085E+03
0.679999E-07	0.354093E+04	0.415043E+11	0.588943E+09	0.107614E+04
BRIDGEWIRE 1				
BURST TIME = 7.299985E-02 MICROSECONDS				
BURST CURRENT = 3.712801 KILOAMPS -- PRIMARY CURRENT				
0.729999E-07	0.371280E+04	0.302322E+11	0.718236E+09	0.170793E+04
0.779998E-07	0.387267E+04	0.338562E+11	0.859154E+09	0.981097E+03
0.829998E-07	0.406683E+04	0.398310E+11	0.101362E+10	0.742115E+03

To obtain a hard copy of the graphics output we press "shift" and "print screen" simultaneously. The result is shown below, where I have pasted the printer record of the input variables on the graph.

It is obvious that the system stores far more energy than is needed to explode the bridgefoil in this example. To rerun the problem with different parameters, simply press any key and the menu shown on the figure below will appear on the screen. If you want to save the graph, be sure to do it before you touch any other keys, otherwise the menu will be written on top of the graph, as is shown below.

DO YOU WANT TO CHANGE ANY INPUT PARAMETERS? Y/N									
? y									
WHICH PARAMETER DO YOU WANT TO CHANGE?									
1--STEP SIZE					10--B=PEAK RESISTIVITY				
2--SYSTEM INDUCTANCE					11--G0-SP ACTION TO BURST				
3--CAPACITANCE					12--S=WIDTH OF RESISTIVITY PEAK				
4--CHARGING VOLTAGE					13--ERROR PER STEP				
5--BRIDGEWIRE DIMENSIONS									
6--SYSTEM RESISTANCE									
7--MAXIMUM TIME									
8--MAXIMUM CURRENT									
9--A=POST-BURST RESISTIVITY									
ENTER THE NUMBER FOR THE DESIRED CHANGE									
? 3									
INPUT CAPACITANCE IN MICROFARADS									
? .25									
DO YOU WANT TO CHANGE ANY INPUT PARAMETERS? Y/N									
? n									

The program will ask you to enter the number of the parameter you wish to change. In the example above, I had previously reduced the charging voltage to 3.5 kV and at this point wanted to reduce the capacitance to 0.25 microfarads as well. One can continue this procedure until all the desired changes have been made. If no more are desired, simply press "enter" and the calculation will begin using the new parameters. The printer prints out all of the changes, but does not list the parameters that have not been changed. The printer output and the graphical hard copy are shown below.

After a number of changes have been made you may wish to start over with a fresh set of parameters. The simplest way to do this is just to reboot the computer by simultaneously pressing the "ctrl", "alt", and "del" keys.

I have been using this code for four or five years and I think it is fairly bug-free. There are a number of options I have not included in the interest of not making the code too complicated. If the code does not do what you want it to do, the BASIC source code is included on the disk and with a little study and, perhaps, a look at Shoup's book that I referenced at the beginning of this document, you should be able to customize it to fit your needs. I have, for example, a version that writes out the current and time values to a disk file for use with a graphics program. This simply involves adding a few I/O statements and recompiling the program.

The code can also be compiled using the Borlund TURBO BASIC compiler. The only change necessary is to change the first statement to CLEAR without any parameters. The Borlund version runs slightly faster, but I have not run it very much so I am less sure that it is bug-free.

I hope you will find this code useful and will appreciate any comments regarding bugs or suggestions for improvements.