SYRINX PROJECT: HPP GENERATORS DEVOTED TO ISENTROPIC COMPRESSION EXPERIMENTS.

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Abstract. Some compact pulsed-current generators are described here. They allow the generation of isentropic compression loading of metals and other materials. The range of pressures achievable is 30-300 kbar for the Explosive Switch Compact Generator (ESCG). This generator consists of a RLC circuit that discharges in a strip (also called plate)-line insulated by dielectric foils. Placed on the end of this strip-line, some material samples can be studied under dynamical loading. Typical dimensions of the tested samples are 1 mm thick, 8mm diameter. A current of 700 kA to 1.6 MA allows some 30-300 kbar ramp pressures generated with a 500ns rise time. The switch used in the ESCG is a linear-wave-explosive switch.

0D circuit and MHD simulations are discussed and compared with experimental results. Diagnostics based on current-voltage and free-surface velocity measurements are presented. Finally, the generation of isentropic compression principles and simulations discussed above are used to analyse the potential of a new compact generator which development is contracted to ITHPP, a French company. This generator should allow us to explore the 100kbar–1Mbar isentropic compression regime in order to study material behavior under dynamic loading for a large range of material and geometry samples.

INTRODUCTION

Isentropic compression waves have been extensively studied in the 70’s. The most widely developed techniques were quasi-isentropic impact experiments using pillows projected by gas-guns (1), and magneto-explosive generators (2). These two techniques were hampered by some problems or restrictions. Since a few years, there has been a new interest in pulsed-current-generators for generation of quasi-isentropic compression experiments (ICE) (3-4). One of the goals of SYRINX project during the past two years -related in the present article- is to study the opportunity to use and/or develop high pulsed power (HPP) generators for ICE.

When a conductor is carrying a current, the magnetic pressure $P$ related to the magnetic field $H$ is $P=\mu_0 H^2/2$, where $\mu_0$ is the magnetic permittivity of vacuum. When the magnetic field is generated by a current $I$ flowing into a perfect plate-line of width $W$, the current-pressure relation becomes:

$$P=(\mu_0/2).(I/W)^2$$

(1)

Theoretically a current of 1MA flowing into a strip-line of 1cm width leads to a pressure of 63 kbar. A generator delivering 5 MA into this same strip-line would create a pressure up to 1.5 Mbar! Although equation (1) must be revised for practical cases, this promising approach has led us to study this type of configuration.
EXPERIMENTAL SETUP

We have attempted to experimentally study two versions of an ESCG which has already delivered a 0.8 MA peak current in its first version and a 1.6 MA peak current in its second version. In its first version, this generator consists of a single 3.95 μF capacitor charged to 70 kV, a strip-line connexion ended by an explosive switch, and a load (Fig.1). In its second version, the number of capacitors is tripled. The energies stored are respectively 9.6 kJ and 29 kJ for the two versions. The whole system occupies a volume of less than 2 m³.

The switch is a linear-wave-explosive switch allowing the current to be discharged in a 8 cm-centimeters-long line with a closing time of a few tens of nanoseconds. Currents up to 1.6 MA have been commuted by this switch. The destruction following the detonation is limited to the consumable parts thanks to an appropriate setup and to the small quantity of explosive involved (a few tens of grams only).

The load is a strip-line whose electrodes are made of copper and are insulated by thin dielectric foils. Typical widths $W$ of these electrodes are 12 mm to 4 mm. Typical gap separating the two load-electrodes (insulated by dielectric foils) are 0.4 to 0.1 mm. Two VISAR free-surface-velocity measurements are done during each shot on one side of one of the two load-electrodes. This number could be increased to four by using both sides of the load. No material sample has been set on the copper electrode in order to be studied. Thus, in the following lines, what we will call “sample” is at present the electrode itself.

Both current and voltage are measured just before the explosive switch with dedicated B-dot and D-dot sensors built at CEG. As they were not properly calibrated in a strip-line configuration, a calibration shot was done for the 3-caps-version of the ESCG, where the reference sensor was a Rogowski coil inserted between the load-electrodes. Temporal resolution and synchronisation of all the sensors and VISAR is about 1ns.

FIGURE 1. Load region and measurement setup.
1- B-dot and D-dot sensors, 2- VISAR heads.

The width of the strip-line (load) electrodes are chosen so that magnetic field distribution can be considered as uniform on the sample surface to better than 3 % and that edge effects don’t affect the experiment. This allows VISAR samples to be studied under 1-D planar compression waves conditions (no edge effects) during the risetime of the first main-pulse of the current.

RESULTS AND ANALYSIS

Nine experiments have been performed with the first version of the ESCG. Only seven experiments have been done till now with the 3 caps-version. The first goal of these shots was to demonstrate the validity of the concepts used in this type of generators: dielectric insulation, explosive switch, and performance (in term of pressure achievable) of the strip-line load-electrodes. They have shown a very good reproducibility of the switch behavior and thus have led to a 0D electrical modelization. The inductances and resistances have been calculated with simple geometrical considerations and the results are in very good agreement with the experimental data (Fig. 2).

The load impedance is supposed variable during the shot. The key points for calculating this variation are the diffusion of magnetic field in the copper of the load-electrodes and the increase of the gap due to the pressure wave during the shot.
We define what we call an “effective gap” $g_{\text{effective}}$ by equations (2):

$$g_{\text{effective}} = g_{(t=0)} + f[d(t), \delta(t)]$$  \hspace{1cm} (2-a)

where $\delta(t)$ is a skin depth and $d(t)$ is the displacement of inner faces of load-electrodes. If one supposes that there is no effective displacement of electrodes during the shot, one has:

$$f[d(t), \delta(t)] = \delta(t)$$  \hspace{1cm} (2-b)

On the other, one can suppose that electrodes stay solid and are pushed by magnetic pressure, hence:

$$f[d(t), \delta(t)] = 2.d(t) + \delta(t)$$  \hspace{1cm} (2-c)

In order to evaluate $\delta(t)$ some MHD calculations have been performed at linear current densities and typical timing scale of our experiments, i.e. between 1 and 2 MA/cm and 500 ns respectively. Different resistivity models have been used: TAPP, RRCK and Burgess (SESAME tables are planned).

Analytical evaluations of inductance and resistance give some values that differs by less than 20% from the value obtained by 2D magneto-dynamic simulations. Notice that ESCG performances are not so affected by the load impedance variations, which justifies the use of the very simple analytical relations.

In Eqs. 2 the displacement of inner faces of load-electrodes is easily calculated by integration of velocity of these electrodes. This integration is performed at each time step of the 0D electrical simulation. The code used is SABER and allows to couple electrical simulations to physical models (flux penetration, velocity increase of inner faces of electrodes, etc...) (5). Figure 3 shows the VISAR data of shot#14 where the thickness of the samples were 1.51mm±6μm and 2.09mm±6μm respectively and the width of the load-electrode was 6mm±20μm.

In order to evaluate the maximum pressure achieved, the deconvolution of one VISAR record was performed with the method of characteristics for the temporal aspect coupled to the equations (3) and (4) of conservation of momentum and mass:

$$d\sigma = \rho_0 D du_p$$  \hspace{1cm} (3)

$$dV = -(V_0/D).du_p$$  \hspace{1cm} (4)

where

$\sigma$= stress in the direction of wave propagation
$V$ (resp. $V_0$)=specific volume (resp. initial specific volume)
$\rho_0$=original density (=1/V_0)
$D$= Lagrangian wave speed
$u_p$=particle velocity=\(u_d/2\) \hspace{1cm} (5)

Eqn. (5) can be used as a first approximation in this deconvolution procedure. Some more accurate relations were chosen here: they were based on analysis of hydrodynamic simulations in which the elasto-plastic behavior of copper was taken into account. The typical error introduced by equation (5) on the pressure result is about 10%.

One can notice that Eqn. (1) needs to be corrected to explain the pressure achieved (250 kbar instead of 450 kbar predicted by Eqn. 1 with a maximum experimental current of 1.6 MA and a plate line of width 6 cm). The corrected equation is:

$$P = (\mu/2).I/W^2 / k_p$$  \hspace{1cm} (6)
where $k_p$ is a factor >1 function of the effective gap given by Eqn. 2-a. The relation $k_p = k_p(gap_{effective})$ is evaluated by 2D magneto-dynamic simulations and finally, one obtains the very simple relation:

$$k_p = a \cdot gap_{effective} + 1$$  \hspace{1cm} (7)

with $a$ is a constant depending only on the initial geometry of electrodes of the strip line (width and thickness).

Finally, the compression loading path of copper can be obtained through equations (3) to (4) and Lagrangian analysis. Figure 4 shows the curve $P=P(\eta)$ where $\eta$ is the compression rate ($\eta=p_0/p$) compared to experimental datas of Sandia National Laboratories (Isentropic) and McQueen datas (4 and 6):

![Figure 4. Pressure vs. compression rate ($p_0/p$) obtained from the VISAR data of Fig. 3 compared to experimental datas.](image)

Hugoniot and isentropic data are in good agreement, except for low pressures. This still needs to be analyzed.

**FUTURE**

The ESCG is a “first step generator”: it allows us to study the opportunity to use strip-line for ICE. The results obtained are very encouraging. Areas like material properties (EOS, phase transitions, polymorphic transitions, etc...) can now be studied by this way. The ESCG is actually a very versatile tool for studying both materials under quasi-isentropic loading and high current density physics. Another application of this generator could be the test of new sensors in a harsh environment (linear current density or magnetic field up to 2 MA/cm). Examples of such sensors are μB-dots or Faraday rotation sensors for current measurement. Another great advantage of this generator is its easiness of use. Thus it is possible to use it for series of experimental campaigns that would mobilize bigger HPP generators elsewhere. For instance, we plan to measure magnetic field diffusion in copper thanks to this ESCG.

A new generator is now being built at CEG: it is based on the same plate-line principle but should deliver a current of about 4 MA in a load of 10 mm width. It should allow us to achieve pressures up to 1 Mbar. It should allow us to study material behavior under dynamic loading for a large range of material and geometry samples.

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**REFERENCES**