

A minimal model to understand the discrepancies between acoustic and electromagnetic emissions in fracturing processes

J Clavijo¹, S Sánchez², and Y Salas³

¹ Escuela Colombiana de Ingeniería Julio Garavito, Bogotá, Colombia

² Universidad de Nariño, Pasto, Colombia

³ Universidad Distrital Francisco José de Caldas, Bogotá, Colombia

E-mail: jorge.clavijo@escuelaing.edu.co

Abstract. Despite their common origin, experiments show that acoustic and electromagnetic emissions evolve in different ways during the fracture processes of brittle materials. It is common to find peaks of acoustic activity without the presence of electromagnetic emissions and *vice versa*, it is possible to find high electromagnetic radiation without significant acoustic activity. As far as we know, there are currently no models that explain these discrepancies in a simple way. In this work we propose a minimal model that is able to generate the frequently observed discrepancies between acoustic and electromagnetic emissions during fracture processes of brittle materials. The model is an electrical version of the fiber bundle model where the fibers are replaced by fuses in a resistor. The resistors are placed on a Wheatstone bridge subjected to a gradually increasing voltage. A capacitor is added to generate charge and discharge processes that will generate the electromagnetic emissions, while the breaking of the fuses will generate the acoustic emissions. The model allows to follow the evolution of acoustic and electromagnetic activities and shows that, despite their common origin, the two phenomena evolve differently.

1. Introduction

The fracture of brittle solids is accompanied by the gradual generation of micro-cracks that can be indirectly inferred by detecting their acoustic emissions (AE) [1]. Although the acoustic emission technique is the dominant method to follow the evolution of micro-cracks, the existence of electromagnetic emissions (EME) is also well known. EME have been detected in ice, rocks, metals and even the Earth's crust [2–4].

The causes of electromagnetic emissions are diverse and several mechanisms have been proposed. Among the most prominent are: electrification of the air contained between fracture faces, movement of charged dislocations [5], electrification of the fracture tip [6], electrification of fracture faces due to abrupt rupture, and polarization of fracture faces due to interaction with mechanical waves (see [7] for a detailed discussion of models). Beyond the differences between these mechanisms, an important component in the generation of EMEs comes from the process of charge recombination through the material, similar to what occurs with the discharge of a capacitor through a resistive element. From this perspective the different mechanisms can be viewed as physical processes that will, in a sense, charge the faces of the micro-cracks while the recombination currents will generate the fields associated with the electromagnetic emissions.

Thus, although each mechanism will have a characteristic signature that will depend on internal processes in the micro-crack, the charge recombination process will depend more on the state of the material and will be a reflection of its state of deterioration.

Surprisingly, there are no statistical models that take into account the generation of EME during fracture processes and its relation with AE. The creation of such models is especially relevant in understanding the frequently reported differences between AE and EME [8]. There are different types of models to explain some aspects of the fracture process in brittle materials. Among these, fiber models have been shown to be successful in the description of abrupt rupture [9, 10], the stress-strain relationship and the avalanche statistics represented through acoustic emissions. In their original conception, a fiber bundle consists of an array of N elastic fibers subjected to a gradually increasing load. Each fiber can withstand a maximum stress above which it will irreversibly break. After the rupture of a fiber the load will be distributed over the remaining surviving fibers.

The characteristics of the fiber models can be reproduced in an electrical analog [11, 12]. The fibers are replaced by ohmic fuses connected in parallel to a voltage source. If a current higher than its threshold flows through a fuse, then the fuse will irreversibly break. Current and voltage are the analogs of stress and strain respectively. The electrical analog has the advantage of being able to naturally introduce capacitive elements, the charging and discharging processes of these elements will produce the EME generating currents. Thus the stimulus for both emissions is the same, reflecting what is observed in the experiments. In this paper we presented a simple model that allows to understand the relation between AE and EME and explain their no so intuitive behavior.

2. Model and justification

To take into account simultaneously acoustic and electromagnetic emissions, we propose a model in which the fuses are part of resistors located in a Wheatstone bridge. Each resistor in the bridge is made of N fuses connected in parallel and each fuse has a current threshold, above which it will be irreversibly broken, the rupture of fuses will simulate the origin of AE. The bridge is subjected to a voltage $V(t)$ that will increase in time. A capacitor is connected to simulate charge and discharge processes, variations of charge in the capacitor will simulate the origin of EME; Figure 1 shows a schematic representation of the model.

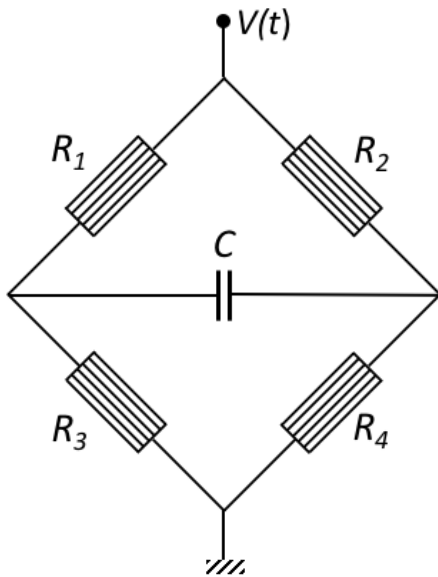


Figure 1. Schematic representation of the model. R_1 , R_2 , R_3 and R_4 are resistors composed by N fuses. Breakdown of fuses represents AE. Charge and discharge processes in the capacitor C are the generators of EME.

In this representation of the material the voltage source will stimulate the breaking of the fuses (AE) which will change the values of the resistors. This will cause the voltage on the capacitor to change and its charge to vary, producing EME. Thus, in a simple way, a single stimulus allows us to understand the generation of both emissions.

However, the key point of the model is that a small number of broken fuses could produce a more intense EME than that generated by a large number of broken fuses. That is, low intensity acoustic emissions could generate much more intense EMEs than those produced by high intensity AE; to see this it is necessary to solve the circuit shown in Figure 1. The problem is reduced to solving a system of first order differential equations where the unknowns are the currents in the resistors and the charge on the capacitor, all as a function of time.

We solved the system and found an analytical solution for this system. Assuming that the initial charge in the capacitor is Q_0 and that the voltage rises abruptly from $V = 0$ to $V = V_f$, we found that the circuit is characterized by a relaxation time (τ) given by Equation (1).

$$\tau = C \frac{R_1 R_2 R_3 + R_1 R_2 R_4 + R_1 R_3 R_4 + R_2 R_3 R_4}{R_1 R_2 + R_2 R_3 + R_1 R_4 + R_3 R_4}, \quad (1)$$

where R_1, R_2, R_3, R_4 and C are as in Figure 1. Variation in time $\dot{Q}(t)$ of the charge in the capacitor is given by Equation (2).

$$\dot{Q}(t) = \frac{CV_f}{\tau} \left(\frac{R_1 R_4 - R_2 R_3}{(R_1 + R_3)(R_2 + R_4)} - \frac{Q_0}{CV_f} \right) e^{-t/\tau}. \quad (2)$$

For economy of space we do not write here the expressions for the currents in the resistors; $\dot{Q}(t)$ in Equation (2) is the generator of EME. Assume that $Q_0 = 0$ in Equation (2). Lets also assume that all resistors take the same value, then, according to Equation (2), $\dot{Q}(t) = 0$. Why is this interesting? Lets suppose that initially all the fuses are identical and intact and that after voltage is increased the same amount (n) of fuses is burned in each resistor. In that case we will have an acoustic event of intensity $4n$, however, according to Equation (2), the associated EME will have no intensity at all. On the other hand, if we have n burned fuses in just one resistor, Equation (2) predicts $\dot{Q}(t) \neq 0$ and therefore we will have an EME. So the model predicts the existence of high intensity AE without the presence of EME and the presence of EME associated with lower intensity AE; this is similar to what is seen in laboratory experiments [8].

3. Methodology

In order to analyze the generation of emissions under gradually increasing loading, we solve the circuit by increasing the voltage V in constant steps ΔV ; after each iteration of the model, the current in each resistor is evaluated and then the current on each fuse is calculated (current division). Fuses with currents above their threshold are eliminated. The number of burned fuses is equivalent to the AE intensity; EME is calculated with Equation (2). The process continues until the current through the circuit drops to zero; the number of fuses per resistor is $N = 4 \times 10^4$ and the threshold for each fuse was taken from an uniform probabilistic distribution in the interval $[10^{-\beta}, 10^{\beta}]$ with $\beta = 6$.

4. Results and discussion

The results of one realization of the model can be seen in Figure 2; the acoustic activity, defined as the number of broken fuses per iteration, is plotted in blue, in logarithmic scale and normalized to its maximum value (left axis). Electromagnetic activity, defined as the maximum value of $\dot{Q}(t)$ at each iteration, is plotted in red and also normalized to its maximum value (right axis); from a general perspective, there are clear differences between the two emissions.

In Figure 2, C1 points to a particular iteration where both emissions take minimum values. This is what is predicted by simple models in which AE and EME are related in a one-to-one correspondence. However, there are iterations where high electromagnetic activity occurs at the time of a minimum of AE activity, this is the case for C2 in Figure 2; in this case a small amount of fuse breakage occurs but the breakage occurs primarily in a resistor giving rise to the unbalance necessary for the generation of EME (see Section 2). C3 and C4 point to iterations where the high acoustic activity does not produce any electromagnetic emission. In this case a large number of fuses are broken, but the number of broken fuses in each resistor is practically the same, leading to a very low EME intensity (see Equation (2)).

In general, it can be seen that the model is able to generate differences between acoustic and electromagnetic emissions even though the source of both is fundamentally the same. Especially interesting is the behavior at the end of the process when the system is about to collapse (see C4 in Figure 2). There, the acoustic activity reaches its highest value indicating the proximity of failure, however the electromagnetic intensity becomes very small. This could generate, on a larger scale, constraints on the field of failure and collapse precursors. In particular, this would be interesting in the context of seismo-electromagnetic phenomena, where the absence of EME during the shock of large earthquakes (a geological-scale AE) has puzzled the scientific community for the last decades [13].

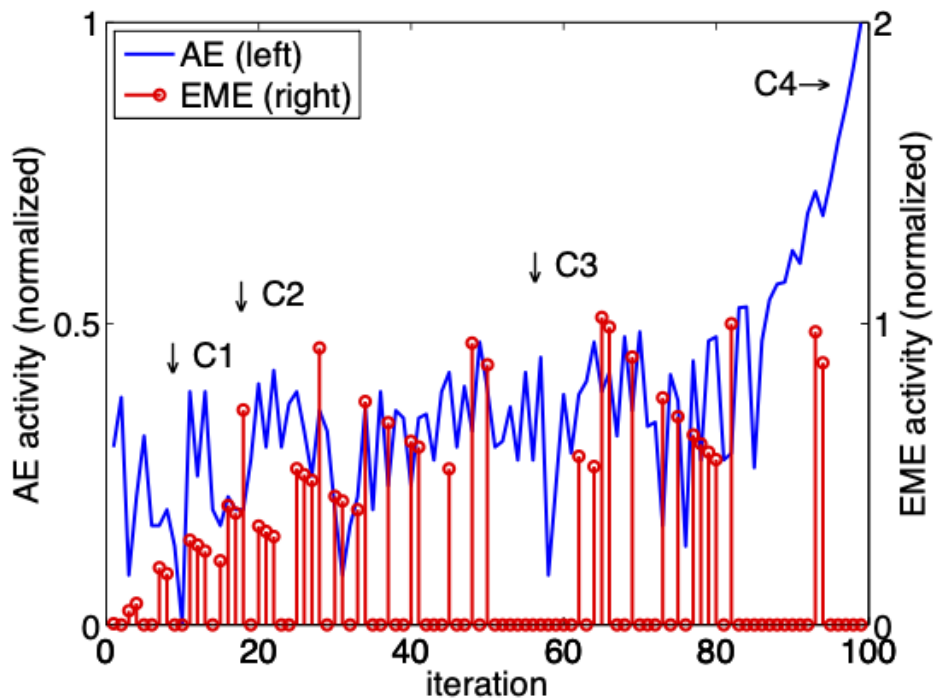


Figure 2. Acoustic activity (number of emissions per iteration, log scale, blue, left axis) and electromagnetic activity (maximum value of $\dot{Q}(t)$, normalized, red, right axis) as a function of the iteration. C1 corresponds to the iteration where both activities coincide at minimum values, C2 shows a high EME with low AE and C3 and C4 point to iterations where AE is high with no significant EME.

5. Conclusions

We have proposed a simple model to explain the differences between acoustic and electromagnetic emissions in fracture processes of brittle materials. The model, an electric version of the fiber bundle models, is capable of take into account the generation of electromagnetic emissions through charge and discharge processes in a capacitor.

The model predicts that, in general, acoustic and electromagnetic emissions are not related in a simple way. High intensity acoustic emissions are not followed by electromagnetic emissions of high amplitude. It is also possible to see high values of electromagnetic intensity at moments of very low acoustic activity. The model then explains some of the discrepancies between both emissions reported in laboratory studies. It is important to keep in mind that it is necessary to analyze more possible scenarios where the model should be tested. In addition, the model should be extended to a network of Whetstone bridges in order to evaluate its scalability and the subsequent extrapolation of results.

References

- [1] Grosse C U, Ohtsu M 2008 *Acoustic Emission Testing* (Berlin: Springer-Verlag) pp 11-18
- [2] Frid V, Vozoff K 2005 Electromagnetic radiation induced by mining rock failure *Int. J. Coal. Geol.* **64**(1) 57-65
- [3] Contoyiannis Y, Potirakis S M, Eftaxias K, Contoyianni L 2015 Tricritical crossover in earthquake preparation by analyzing preseismic electromagnetic emissions *J. Geodyn.* **84** 40-54
- [4] Tzani A, Vallianatos F 2002 A physical model of electrical earthquake precursors due to crack propagation and the motion of charged edge dislocations *Seismo Electromagnetics: Lithosphere-Atmosphere-Ionosphere Coupling* ed Hayakawa M, Molchanov O A (Tokyo: Terrapub) pp 117-130
- [5] Gernets A A, Makarets M V, Koshevaya S V, Grimalsky V V, Romero D J, Kotsarenko A N 2004 Electromagnetic emission caused by the fracturing of piezoelectric crystals with an arbitrarily oriented moving crack *Physics and Chemistry of the Earth* **29**(4-9) 463-472
- [6] Gershenzon N, Zilpimiani D, Maguladze P 1985 Electromagnetic radiation from crack tip during ionic crystals fracture *Dokl. Akad. Nauk SSSR* **248** 1077-1081
- [7] Rabinovitch A, Frid V, Bahat D 2007 Surface oscillations: a possible source of fracture induced electromagnetic radiation *Tectonophysics* **431**(1-4) 15-21
- [8] Clavijo J, Wang H, Sánchez S 2019 Observation of significant differences between electromagnetic and acoustic emissions during fracture processes: a study on rocks under compression loading *J. Phys. Conf. Ser.* **1386**(1) 012107
- [9] Pradhan S, Hansen A, Chakrabarti B K 2010 Failure processes in elastic fiber bundles *Rev. Mod. Phys.* **82**(1) 499
- [10] Hansen A, Hemmer P C, Pradhan S 2015 *The Fiber Bundle Model: Modeling Failure in Materials* (Weinheim: Wiley-VCH) pp 1-8
- [11] de Arcangelis L, Redner S, Herrmann H J 1985 A random fuse model for breaking processes *J. physique, Lett.* **46**(13) 585-590
- [12] Moretti P, Dietemann B, Esfandiary N, Zaiser M 2018 Avalanche precursors of failure in hierarchical fuse networks *Sci. Rep.* **8**(1) 1-7
- [13] Hayakawa M, Hobara Y 2010 Current status of seismo-electromagnetics for short-term earthquake prediction *Geomat. Nat. Hazards Risk* **1**(2) 115-155