# Crustal stress and acoustic emission (*AE*)

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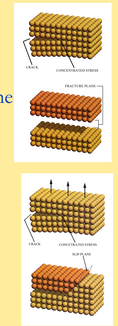
## Structure of the poster

1. The physical principle
2. Data handling – algorithms
3. Direct applications
4. Indirect applications
5. Some relevant practical implications

## The physical principle The source

- ***An AE source*** is associated with the release of energy from the yield of some chemical bonds within some crystal structure
- ***The reaction chain*** concept applies: one additional chemical bond is more likely to yield close to the point where the mechanical strength of the solid object is comparatively weaker due to the presence of some previous flaw

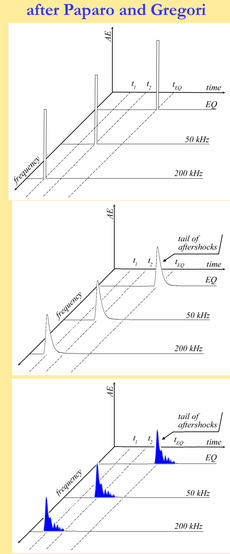



## The time sequence of the frequency of the observed *AE*

- Small-size flaws are first detected, associated with comparatively *HF AE*
- Smaller flaws coalesce into larger ones, and release *LF AE*
- One example is enlightening, and it applies to every technological application: seismic events
- An *HF AE* (at ~ *200 kHz*) paroxysm, and later on a *LF AE* (at ~ *25 kHz*) paroxysm, precede ***by several months*** the final shock (at ~ *0.5 ÷ 1. Hz*)
- Analogous paroxysms range from the ultrasound through the sound band
- The seismic roar precedes the shock by ***a few tens*** to ***several tens seconds***
- The vibration of some specific components of buildings (e.g. glass of windows) precedes the shock by ***a few seconds***

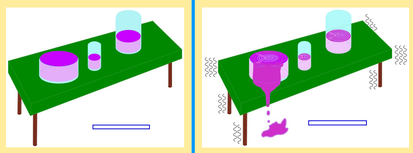
- **As a first order approximation, the phenomenon can be depicted in terms of Dirac δ-functions**
- **Upon closer physical consideration, every δ-function ought to be substituted by a lognormal distribution**
- **An eventual externally applied additional effect (such as e.g. tidal modulation) sometimes results into an apparent trend looking like a damped oscillation**

## The bulk of the frequency of the observed *AE* decreases *vs.* time after Paparo and Gregori




## Indirect applications

- Sometimes, we deal with structures that cannot be likened to a unique solid body – e.g. think about a terrain with landslide hazard, or about a slab of Earth's crust, or about a permanent road or railway, etc.
- We need for some "solid" large object - either natural or even manmade – which can be likened to a probe inserted into the non-solid structure
- Whenever the non-solid structure is affected by some structural change, implying a variation of its stress field, such stress shall be transferred to the "solid" probe
- Monitoring such "solid" probe is therefore an indirect way of monitoring the non-solid structure
- That is, the "solid" structure is to be conceived as a component of the sensor system used as measuring device, altogether with sensor, data logger etc.
- Consider e.g. the case history of a table wine some glasses more or less replenished with wine ….
- Glasses appear teleconnected, although they are independent systems



## Direct applications

- Every "solid" structure, either in metal, or in rock, or in concrete, etc. can be directly monitored
- In general, the *AE* signal suffers by a lesser damping
- Hence, the *AE* sensor gives a significant information about processes occurring within a reasonably large spatial range
- In the case of structure of large dimension, such as buildings, large machineries, bridges, dams, ships, airplanes, cranes, pipelines, etc., several *AE* sensors shall be put in such a way as to monitor the entire structure with the required detail
- In every case history, the *AE* damping must be estimated in order to assess the number of sensors to be operated

## Relevant practical applications

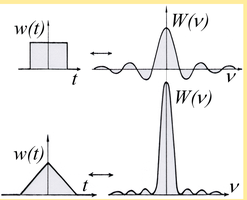
- Working security (buildings, machineries, etc.)
- Old building hazard & historical monument preservation
- Crustal stress propagation (earthquake precursors, volcanoes monitoring, etc.)
- It is of little help, if any, monitoring an earthquake while it occurs
- You must rather monitor with some long time in advance the crustal stress that precedes the occurrence of the earthquake
- Several phenomena related to geodynamics and to several kinds of catastrophes (including soil exhalation, triggering and powering El Niño, or tremendously devastating hurricanes, etc.) cannot be significantly investigated, as a catastrophe is an extreme phenomenon
- *AE* do provide an excellent tool for improving the time resolution of the monitoring of environmental phenomena, with such specific perspective
- Such other key items are ultimately related to the possibility of monitoring in real time the stress propagation through the Earth's crust, implying time variations of soil porosity, hence of degassing.
- Every present model for climate and environment neglects the role of the space and time gradient of the release of endogenous energy
- Research in such direction is presently actively in progress in cooperation with other scientists from different countries all over the world
- Some specific such case histories are e.g.:
  - hurricanes
  - El Niño, and their relation *vs.* earthquakes
  - soil exhalation
  - ice sheet melt *vs.* earthquakes
  - astronomical forcing and crustal stress

## Data handling – algorithms

- search for outliers
- analyses
  - $\mathcal{F}$ (the time variation of the applied external action)
  - $\mathcal{H}$ (the "hammer effect", i.e. "forcing" *vs.* "relaxation" conditions)
  - $\mathcal{T}$ (the role of time, ageing of materials, the capability of matter to react)
  - $\boldsymbol{O}$ (outliers, the way matter reacts)

$\mathcal{F}$ (the time variation of the applied external action)

- The *AE* response is not linear with respect to the applied action
- However, a greater *AE* intensity corresponds to a greater applied action
- Therefore, after applying the rejection of outliers, evaluate a moving average
- It should be recommended applying a weighted moving average, e.g by applying most simply a triangular system function




**Running average with either rectangular or Triangular weigh function**
Weigh functions (and their respective associated system functions) for computing a moving weighted average

## The search for outliers –

With no outlier rejection, several algorithms result severely non-robust.
Even very few outliers can lead to misleading results.
Outliers MUST be rejected

## The rejection of outliers

- Draw the frequency distribution of the **entire** given dataset
- Check whether it is Gaussian or not
- Reject the datum that has the **largest deviation** with respect to the average of the distribution
- The Gaussianicity improves
- Quantify, i.e. give a quantitative measurement, of the degree of Gaussianicity
- **Repeat iteratively** the tentative rejection of the datum that has a comparatively larger deviation
- If the original dataset actually contained outliers,
- whenever we have rejected **all** such outliers, the Gaussianicity must improve in a step-wise way
- In this way, we have **selected and rejected** outliers

## Investigating Gaussianicity and quantifying it

- Investigating it: probit diagram

Quatifying it: define an index

- The Chauvenet rejection criterion
- the $\mathcal{B}$ parameter
- the *95%* confidence limit

**Best suited : the $\mathcal{B}$ parameter**

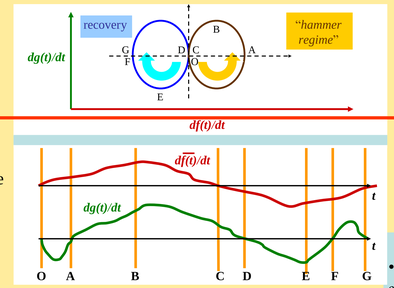
- The original data series contains $N_k$ elements, with *k=0*
- Evaluate its mean $\mu_k$ and rms $\sigma_k$
- Call $\mathcal{B}_k$ the $N_k$-th root of the (Gauss) likelihood function
- Reject the datum with the maximum deviation with respect to $\mu_k$. Thus, the remaining data series contains $N_{k-1} = N_k - 1$ elements

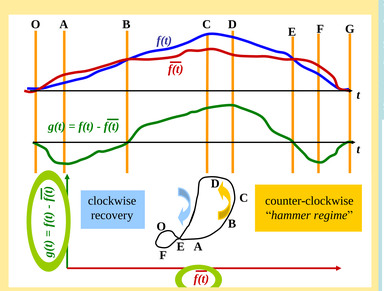
- Evaluate several *k=0, 1, 2, ….*
- Plot $\mathcal{B}_k$ *vs.* *k*, and check that, owing to definition, it must always increase
- When the last outlier has been rejected, such $\mathcal{B}_k$ *vs.* k plot shall display an abrupt step-like increase

$\mathcal{H}$ (the "hammer effect", i.e. "forcing" *vs.* "relaxation" conditions)

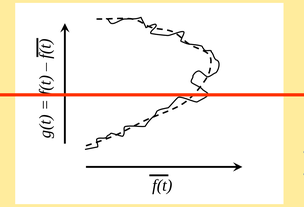
- The system can emit *AE* whenever it is subject to an external forcing
- Otherwise it can emit *AE* whenever it is relaxing and searching for a new equilibrium after havign suffered by an external forcing
- It is possible to define an instant index *H=+1* for forcing condition, and *H=-1* for relaxation condition, while *H=0* is indeterminate

The following plots permit recognizing whether the system is experiencing a forcing condition ("hammer regime") or a relaxation condition ("recovery")



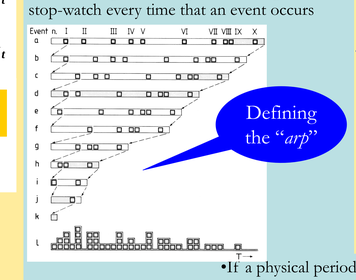




- The parameter *H* can be computed at every time instant *t*
- The final plot *H(t) vs. t* will display some scatter
- But, the physics of the process shall result very clear after applying a suitable smoothing *vs. t*




## The $\mathcal{ARP}$ operator

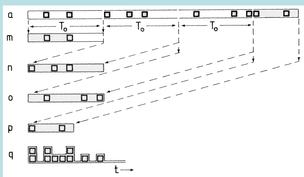
- Given a time series of point-like events (such as e.g. the time series of outliers)
- Construct a histogram, by applying the superposed epoch criterion
- That is, superpose several data series generated from the original one, upon restarting anew the stop-watch every time that an event occurs




$\mathcal{T}$ (the role of time, ageing of materials, the capability of matter to react)

- No "ideal" elastic body exists
- Some crystal bonds always yield, micro-flaws are generated, and progressively increase their size
- Every material is ageing, and with ageing its performance worsens
- The fractal dimension $D_f$ of the time series of the recorded *AE* is en excellent index of such ageing
- When $D_f = 0$ the *AE* sources are randomly distributed in 3D space. Every yielding crystal bond has no memory about the preceding yielding bonds
- When $D_f > 0$ (although, owing to definition, it is always $D_f \leq 1$) the *AE* sources get progressively clustered in space around a 2D plane, which is the cleavage plane of the crystal structure. Every yielding crystal bond has a progressively increasing clear memory about the preceding yielding bonds, as a new bond yields with a higher probability of occurrence whenever it is close to a previously yielded bond.

- If a physical periodicity of period *T0* exists
- The final histogram (which is called ARP) shall display peaks at abscissas *T0, 2T0, 3T0, …., kT0, …*
- Then, evaluate the *"cycle diagram"* associated with the period *T0*
- Subtract from the original data series an ideal periodic time series, generated by putting several cycle diagrams in a time sequence
- Evaluate the residual
- Apply ARP to the series of such residuals
- Evaluate a new periodicity *T1*
- Make its cycle diagram
- Evaluate a new residual, etc.




$\boldsymbol{O}$ (outliers, the way matter reacts)

- Based on practical evaluation, the outlier series clearly resulted to contain an indication of the nature of the material
- That is, outliers are not randomly occurring *vs.* time
- Outliers are deviations of the behaviour of the material compared to a symmetric distribution (such as a normal distribution)
- That is, an outlier denotes a "tail" of a lognormal distribution
- Therefore, analysing the time series of the outliers is indicative of the intrinsic physical features of the system
- For instance, in the case of *AE* records collected in the field, the *AE* time series displays several spectral lines of the Earth's tides
- In the case of a technological application to some given material, the outliers ought to be indicative of specific crystallographic features of the material
- Investigations are in progress
- The algorithm for such investigation is the operator ARP

## References COMPLETARE!!!!!!!!!!!!!!!!!!!

Gregori, G. P., and Paparo, G., 2006. The Stromboli crisis of 28÷30 December 2002. Acta Geod. Geophys. Hung., 41, 2, pp. 273-287.
Paparo, G., Gregori, G. P., Taloni, A. and Coppa, U., 2004. Acoustic emissions (AE) and the energy supply to Vesuvius – 'Inflation' and 'deflation' times. Acta Geod. Geophys. Hung., 40, 4, pp. 471-480.