TEG 097X: Electrochemical techniques for measuring corrosion

Tutorials on Electrochemical Measurements for Monitoring Corrosion

ELECTROCHEMICAL NOISE

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ECG-COMON (Round-Robin tests, noise guideline)

Corrosion 2018 – Phoenix – April 15, 2018

Outline of the presentation

- Generalities on Electrochemical Noise: origins, definition, examples…
- Electrochemical Noise Analysis: time domain, frequency domain
- Measurement technique:
  - various measurement problems
  - validation of the EN measurement
- Corrosion monitoring with noise resistance and noise impedance
- Measurement of electrolyte resistance fluctuations
- Conclusions and further information

What is Electrochemical Noise?

- spontaneous fluctuations of
  - potential (galvanostatic control) 1 WE
  - current (potentiostatic control) 1 WE
  - potential and current (ZRA) 2 WE
- measured at corrosion potential (monitoring purpose)

  or not (ex: passive domain to study pitting corrosion)
- no external signal applied (non-perturbative technique)
- main idea for field applications:

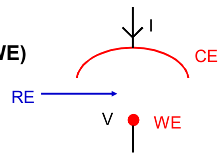
  "listening" the noise to detect localized corrosion

Origins of the noise

- for any physical system:
  - thermal noise (thermal vibrations of electrons)
  - shot noise (quantized nature of charge carriers)
  - 1/f noise (various origins, not clear)
- in the corrosion domain:
  - general corrosion
  - metastable pitting corrosion
  - other localized corrosion: crevice, IGSCC, TGSCC, cavitation…)
  - hydrogen evolution (acidic media)
  - passage of solid particles (erosion) or oil droplets in brine…
  - flows enhance EN if corrosion controlled by mass transport
  - etc, etc…

Electrochemical noise with 1 WE

One single working electrode (WE)



- galvanostatic control

• $I = I_o$: $V = V_o + v(t)$ **v(t) = voltage noise**

(ex: $I_o = 0$ at corrosion potential)

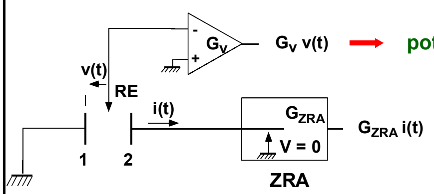
- potentiostatic control

• $V = V_o$: $I = I_o + i(t)$ **i(t) = current noise**

→ **v(t) or i(t): information on the electrochemical processes**

Electrochemical noise with 2 WEs

2 identical working electrodes: Eden, Hladky, John, Dawson, Corrosion / 86, Paper 274



→ **potential noise v(t)**

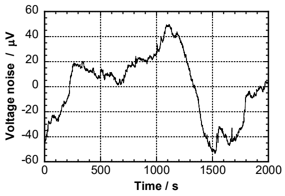
→ **current noise i(t)**

• RE : true RE (SCE, SSE...) or 3[rd] identical electrode

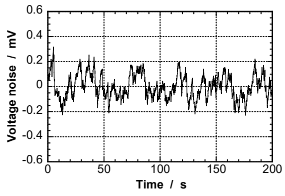
Some examples in corrosion

at corrosion potential ($I_o = 0$)

copper in 1M KCl



iron in 1M H_2SO_4



low level of noise:
copper dissolution
(1 WE)

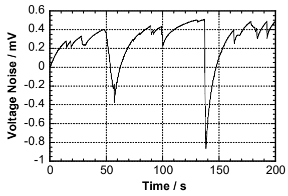
high level of noise:
H_2 bubble evolution
(1 WE)

no visible transients

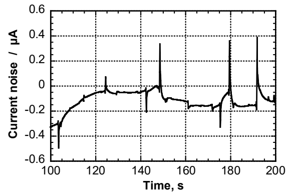
Some examples in corrosion

at corrosion potential ($I_o = 0$)

Al in 1M KCl



iron in 1M Na_2SO_4 (pH 3)



high level of noise:
pits
(1 WE)

high level of noise:
H_2 bubble evolution
(2 WE)

visible transients

Electrochemical Noise Analysis

several methods (only "standard" methods are presented)

- analysis in the time domain: transient shape, SD, R_n...
- analysis in the frequency domain: PSD

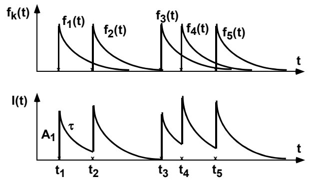
aim:

- investigate fundamental aspects of corrosion: mechanism, pitting domain…
- corrosion monitoring (in the field) :
  - corrosion rate estimation
  - discriminate between various types of corrosion: uniform, pitting, intergranular, SCC...

Time domain analysis

Study of the current and potential transients

ex: metastable pits at applied (passive) potential (V_o)



$$I(t) = \sum_i f_i(t - t_i)$$

- shape of the transients
- t_i: mean number of pits generated per second at V_o
  → pitting potential, survival probability…
- A_i → electrical charge implied in a single pit
- τ: repassivation time constant

Time domain analysis

Standard deviation and root mean square (RMS): $I = I_o + i(t)$

- standard deviation $\sigma_i = \sqrt{<i^2(t)>}$
- root mean square $I_{rms} = \sqrt{<I^2(t)>} = \sqrt{I_o^2 + \sigma_i^2}$

idea: estimation of the corrosion rate from σ_v or σ_i
(not possible with a single WE)

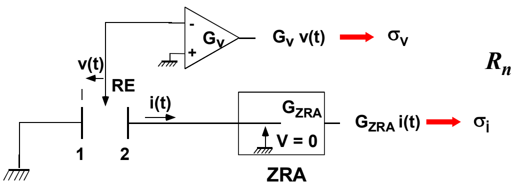
"Pitting index": $PI = \dfrac{\sigma_i}{I_{rms}} = \dfrac{\sigma_i}{\sqrt{I_o^2 + \sigma_i^2}}$ → $0 \le PI \le 1$

- uniform corrosion: $\sigma_i << I_o$ → $PI \approx 0$
- localized corrosion: $\sigma_i >> I_o$ → $PI \approx 1$

but: conflicting results on the estimation of the degree of localized corrosion from PI

Time domain analysis

Calculation of the noise resistance (2 identical WEs)



$$R_n = \frac{\sigma_v}{\sigma_i}$$

- RE : true RE or 3rd identical electrode
- experimentally: $R_n \approx R_p$ → $i_{corr} = \dfrac{B}{R_n}$
- proposed for corrosion monitoring (in the field) at a lower cost than EIS, LPR

Analysis in the frequency domain: power spectral density

time domain — Fourier transform / Inverse Fourier T. — frequency domain

$x(t)$

$$X(f) = \int_{-\infty}^{+\infty} x(t)\, e^{-2i\pi f t}\, dt$$

Some examples

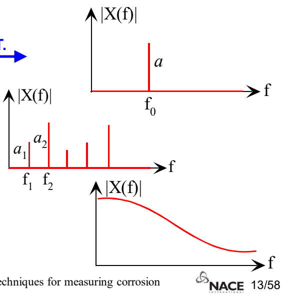
1) pure sine wave — F. T.

$x(t) = a \sin(2\pi f_0 t + \phi)$

2) periodic signal — F. T.

$x(t) = \sum_i a_i \sin(2\pi f_i t + \phi_i)$

3) any signal (noise) — F. T.

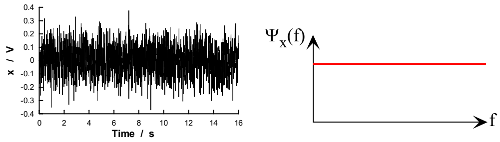


Analysis in the frequency domain: power spectral density

T = acquisition time

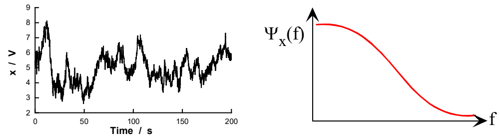
PSD: $\Psi_x(f) = \frac{2}{T} \left| X(f) \right|^2$

white noise

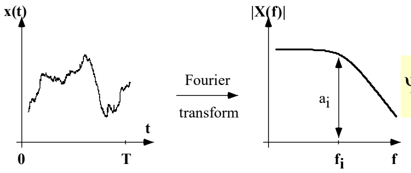


the most random signal

non-white noise



Analysis in the frequency domain: power spectral density



PSD:

$$\Psi_x(f) = \frac{2}{T} \left| X(f) \right|^2$$

x(t) = summation of sine waves $a_i \sin(2\pi f_i t + \phi_i)$

- at low frequency: a_i high ⟷ large slow x variations
- at high frequency: a_i low ⟷ small fast x variations

• maximum entropy method (MEM): dangerous! never use it alone (see Ref.)

• information from:
- amplitude of the low-frequency plateau
- cut-off frequency
- slope of the decrease

Algorithm for PSD calculation with FFT

loop N times

{

acquisition of M data points of $x(t)$

linear detrending or not

remove the mean value of x (not informative since corresponds to frequency 0)

multiply by the Hann window

FFT

PSD calculation: $\Psi_x(m\Delta f) = \frac{2}{T} \left| X_T(m\Delta f) \right|^2 = \frac{2}{M} \Delta t \left| \sum_{n=0}^{M-1} x(n\Delta t)\, e^{-2i\pi mn/M} \right|^2$

}

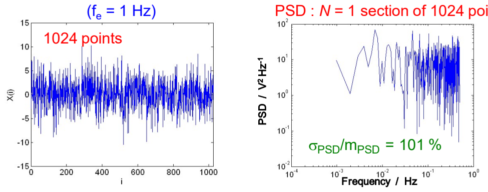
average the N PSDs

if Hann: multiply the result by 8/3.

Example: digital white noise (randn in Matlab)

(f_e = 1 Hz)

PSD : N = 1 section of 1024 points

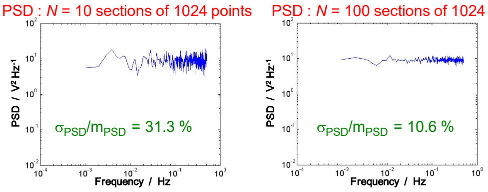


relative error:

$$\varepsilon = \frac{1}{\sqrt{N}}$$

PSD : N = 10 sections of 1024 points

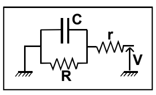
PSD : N = 100 sections of 1024 points



Example: thermal voltage noise of a R-C circuit

• measurement without ZRA, galvanostat (V amplifier only)

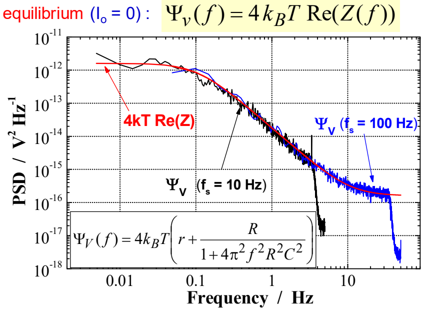
• thermodynamic equilibrium (I_o = 0) : $\Psi_V(f) = 4 k_B T\, \mathrm{Re}(Z(f))$



R = 100 MΩ

r = 10 kΩ

C = 15 nF

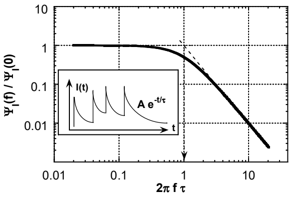


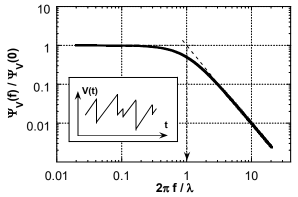
$$\Psi_V(f) = 4 k_B T \left(r + \frac{R}{1 + 4\pi^2 f^2 R^2 C^2} \right)$$

• good overlap of the 2 PSDs (validation of EN measurement)

Frequency domain analysis

pitting corrosion | **gas-evolving electrode**





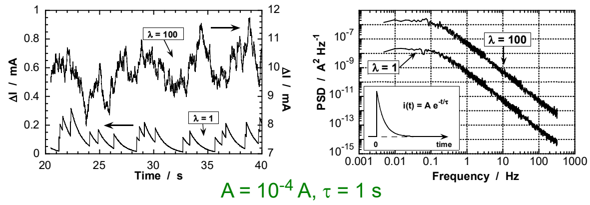
$$\Psi_I(f) = 2\lambda \frac{\langle A^2 \rangle \tau^2}{1 + 4\pi^2 f^2 \tau^2} \qquad \Psi_V(f) = \frac{2\lambda < A^2 >}{\lambda^2 + 4\pi^2 f^2}$$

PSD interpretation is difficult

Frequency domain analysis

Poisson process (shot noise): independent time t_i

$$\Psi_I(f) = 2\lambda \, |i(f)|^2 = 2\lambda \frac{A^2 \tau^2}{1 + 4\pi^2 f^2 \tau^2}$$

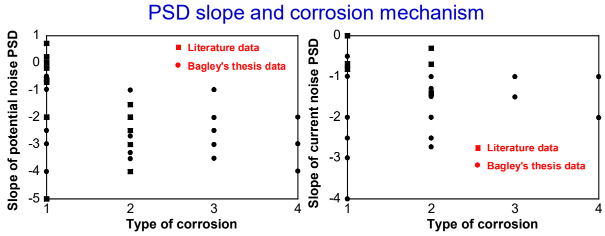


$A = 10^{-4}$ A, $\tau = 1$ s

- impossible to see the elementary transients when numerous
- the PSD shape only depends on the shape of the transient

Frequency domain analysis

PSD slope and corrosion mechanism



1: uniform corrosion
2: pitting corrosion
3: corrosion with cracks
4: pits and cracks

(R. A. Cottis, Corrosion, 57 (2001) p. 265)

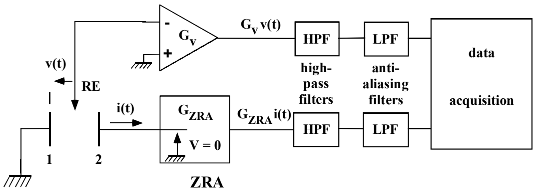
no relationship between PSD slope and corrosion mechanism

Measurement technique

-

Various measurement problems

Electrochemical noise measurement

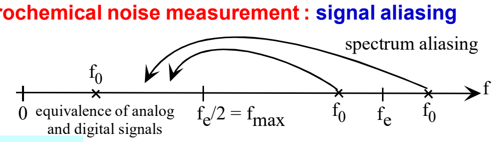


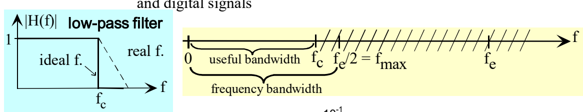
Measurement problems:

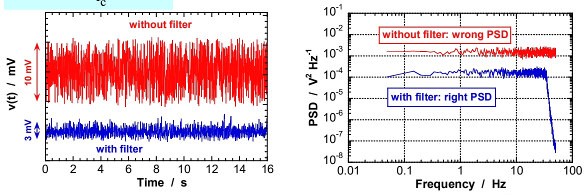
- low amplitude of the signals (low-noise instrumentation)
- low-pass filtering to avoid signal aliasing
- signal windowing to measure the PSD (Hann window)
- non-stationarity of the noise (signal drift)

Electrochemical noise measurement : signal aliasing

$$f_e = \frac{1}{\Delta t}$$



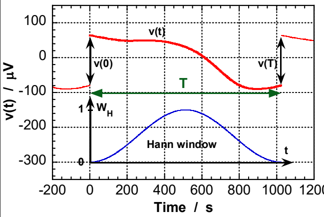




Electrochemical noise measurement

signal windowing for PSD measurement

- the FFT assumes the signal periodicity from t = -∞ to +∞
- parasitic jumps v(T) at t = T that give a hf component

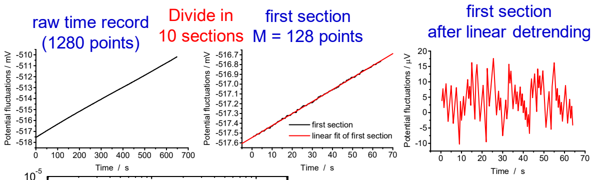


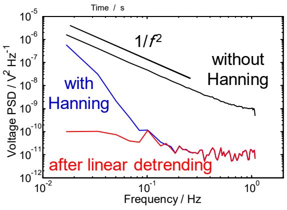
$$w(n\Delta t) = 0.5\left(1-\cos\left(\frac{2\pi n\Delta t}{T}\right)\right)$$

- v(nΔt) × w(nΔt) before FFT
- multiply the PSD by 8/3

Electrochemical noise measurement

signal windowing for PSD measurement





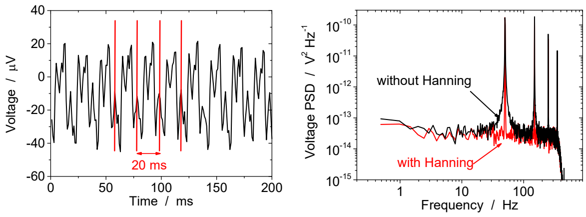
$$\Psi_{V+drift} = \Psi_V + \frac{a^2 T}{2\pi^2 f^2}$$

smooth (wrong) spectra

signal drift

Electrochemical noise measurement

signal windowing when periodic components (50 or 60 Hz) in the noise (PSD measurement at high sampling frequency)

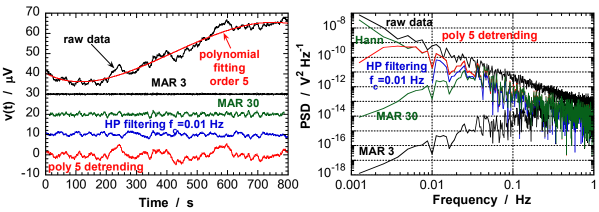


→ Hanning gives narrower spectral peaks at 50 Hz (60 Hz) and harmonics

Electrochemical noise measurement

non-stationarity of the noise (signal drift)

Corrosion of Al-Zn-Mg-Cu alloy at E_{corr} in 0.5 M NaCl



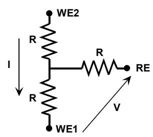
- strong influence of the drift on standard deviation and PSD
- “moving average removal” (MAR) : not recommended
- good results with high-pass filtering or polynomial detrending

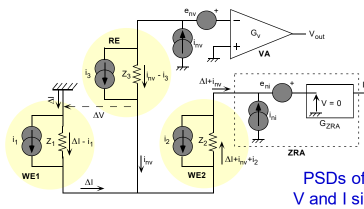
Validation of the EN measurement

Validation: thermal noise of resistors with ZRA

- experiment easy to perform

  - ZRA mode with 3 identical resistors (R = 100 Ω to 100 MΩ)





if the noises due to ZRA and voltage amplifier are neglected

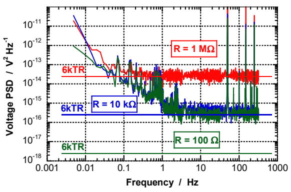
PSDs of the V and I signals:

$$\Psi_V = 6kTR$$

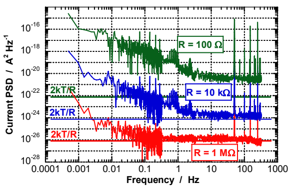
$$\Psi_I = 2kT\frac{1}{R}$$

Validation: thermal noise of resistors with ZRA

voltage noise



current noise

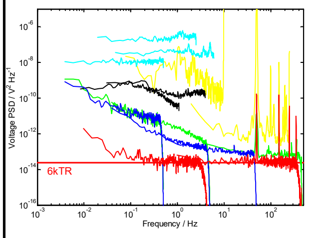


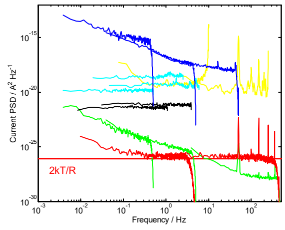
thermal voltage noise measured
- for R = 1 MΩ above 0.5 Hz
- for R = 10 kΩ above 10 Hz
- not for R = 100 Ω (too low)

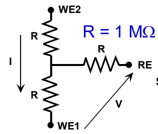
thermal current noise measured
- for R = 1 MΩ above 0.1 Hz
- for R = 10 kΩ above 10 Hz
- not for R = 100 Ω (too low)

Validation: Round-Robin test (ECG-COMON, 2008)

European Cooperative Group on Corrosion Monitoring of Nuclear Materials







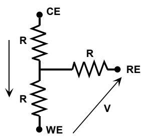
R = 1 MΩ

Very few good EN measurements with commercial equipments (2008) !!

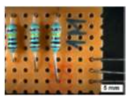
see **"Reliability of electrochemical noise measurements: Results of round-robin testing on electrochemical noise", R-W Bosch et al., Electrochimica Acta, 120 (2014) 379**

Round-Robin on Electrochemical Noise #12 (June 2017)

- 3 identical resistors in star arrangement (ZRA mode)
- R = 1 MΩ and R = 100 MΩ
- thermal noise : low but known (Ψ_V = 6kTR, Ψ_I = 2kT/R)



- 20 participants: 3 manufacturers
-24 data sets received : 11 Gamry, 4 Solartron, 2 Bio-logic, 4 IPS, 1 Maxion, 1 PAR (Ametek), 1 ACM



total: 149 files, 298 time records, 298 PSD

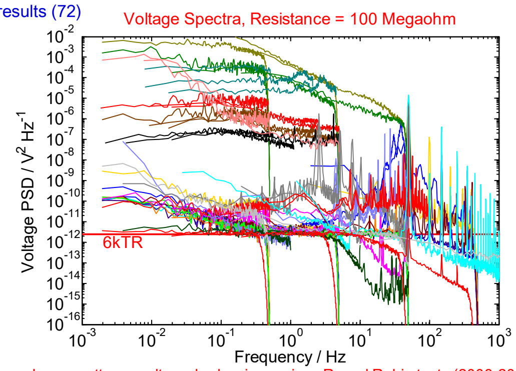
Analysis performed in frequency domain (FFT as in last RR test):
- only way to validate EN measurements
- measurements have to be performed at different sampling frequencies (3 or 4 for all participants)

Aim: compare the new results with those measured before 2008

Round-Robin on Electrochemical Noise #12 (June 2017)

All results (72)

Voltage Spectra, Resistance = 100 Megaohm



large scatter: results as bad as in previous Round Robin tests (2008-2016)

Some advices for EN measurements

- validation of EN measurements can only be performed in the frequency domain (PSD)
- it is important to perform measurements at different sampling rates to check the overlapping of the PSDs
- never use the auto-range of the measurement device

see "Guideline for an assessment of electrochemical noise measurement devices", S. Ritter, F. Huet, R.A. Cottis, Materials and Corrosion, 63 (2012) 297

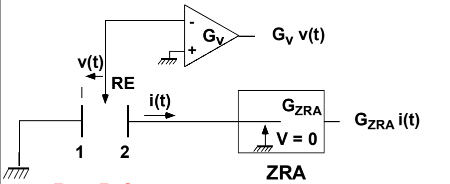
based on ECG-COMON's work (www.ecg-comon.org)

- on the website (free access): psd_ECG-COMON.exe for PSD calculation

- C2018-11042: "Electrochemical Noise - Guidance for Improving Measurements and Data Analysis", F. Huet, K. Ngo (Monday, 9:10, room 228 A-B)
- C2018-11040: "Electrochemical Noise Measurements with Dummy Cells: Evaluation of a Round-Robin Test Series", F. Huet, S. Ritter (Wednesday, 9:25, room 131 A-B)

Corrosion monitoring with noise resistance and noise impedance

Corrosion monitoring with EN



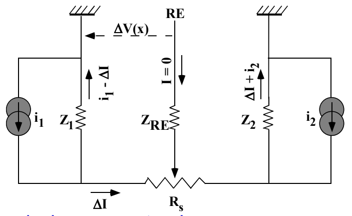
$R_n = \dfrac{\sigma_V}{\sigma_i}$

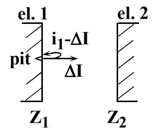
if $R_n = R_p$

$i_{corr} = \dfrac{B}{R_n}$

- $R_n = R_p$?
- model + experiments with U. Bertocci
  (6 papers in J. Electrochem. Soc. since 1997)
- 2 cases: - 2 identical electrodes + true RE (scheme #1)
  - 3 identical electrodes (scheme #2)
- noise impedance: $Z_n(f) = \sqrt{\dfrac{\Psi_V(f)}{\Psi_I(f)}}$

Corrosion monitoring with EN





- i_1, i_2 = current noise sources (cannot be measured) ← bubbles, pits, cracks…
- only ΔI(t) and ΔV(t) can be measured
- Ohm's law in the frequency domain (for $R_s \approx 0$):
  - for ΔI: $-Z_1 (i_1-\Delta I)+Z_2(\Delta I+i_2)=0$
  - for ΔV: $\Delta V = -Z_1 (i_1-\Delta I)$

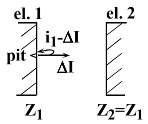
Corrosion monitoring with EN: current distribution

$-Z_1 (i_1-\Delta I)+Z_2(\Delta I+i_2)=0$ gives $\Delta I(f) = \dfrac{Z_1(f) i_1(f) - Z_2(f) i_2(f)}{Z_1(f)+Z_2(f)}$

- for 2 identical WEs: $Z_1 = Z_2$ (= Z)

$\Delta I(f) = \frac{1}{2}(i_1(f) - i_2(f))$ or $\Delta I(t) = \frac{1}{2}(i_1(t) - i_2(t))$

- with a pit on WE #1 and nothing on WE #2 ($i_2 = 0$)



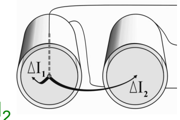
$\Delta I(t) = \frac{1}{2} i_1(t)$

$i_1(t) - \Delta I(t) = \frac{1}{2} i_1(t)$

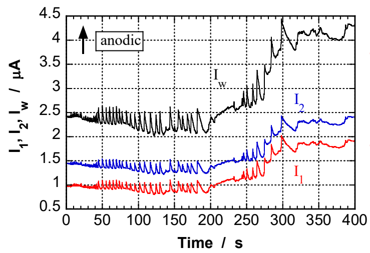
only half of the current i_1 is measured by the ZRA!

Corrosion monitoring with EN: current distribution

- WE #1 and 2 : SS316L, diameter 1.5 cm
- WE #3 : iron, diameter 250 µm
- 0,06 M NaCl



- 3 ZRA for measuring the 3 currents I_w, I_1, I_2



- cathodic processes on WE #1 and #2 $\Delta I_1 = \Delta I_2$
- current measured by the ZRA: $\Delta I_2 = \frac{1}{2} \Delta I_w$

Corrosion monitoring with EN: noise impedance

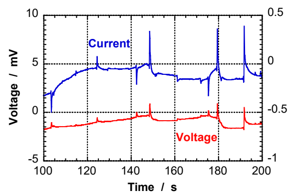
- for 2 identical WEs (scheme #1): $\Delta I(f) = \frac{1}{2}(i_1(f) - i_2(f))$
- $\Delta V = -Z_1 (i_1-\Delta I)$ gives $\Delta V(f) = -\dfrac{Z(f)}{2}(i_1(f) + i_2(f))$
- hence the PSDs: $\Psi_I(f) = \frac{1}{4}(\Psi_{i_1}(f) + \Psi_{i_2}(f))$

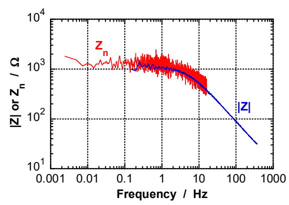
$\Psi_V(f) = \dfrac{|Z(f)|^2}{4}(\Psi_{i_1}(f) + \Psi_{i_2}(f))$

- noise impedance: $Z_n(f) = \sqrt{\dfrac{\Psi_V(f)}{\Psi_I(f)}} = |Z(f)|$
  - ∀ the origin of the noise : bubbles, pits, cracks…
  - ∀ the level of the noises i_1, i_2
  - measurement of |Z| from the internal noise (without external excitation)

Corrosion monitoring with EN: noise impedance

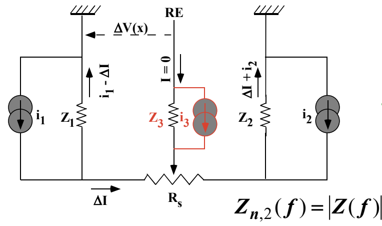
- corrosion of iron in 1M Na_2SO_4 (pH 3), RE = SSE (scheme #1)





- noise due to hydrogen-bubble evolution
- $Z_{n,1}(f) = |Z(f)|$ ← 2 identical WEs + true RE

Corrosion monitoring with EN: 3 identical WEs (scheme #2)



$Z_1 = Z_2 = Z_3$ (= Z)

$$Z_{n,2}(f) = |Z(f)|\sqrt{1+\frac{4\Psi_{i_3}(f)}{\Psi_{i_1}(f)+\Psi_{i_2}(f)}}$$

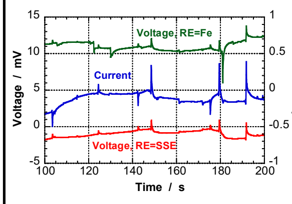
- Z_n depends on the noise of each electrode
- if the electrodes are identically noisy (same PSD):

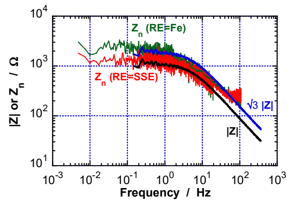
$$Z_{n,2}(f) = \sqrt{3}\,|Z(f)|$$

- doubtful assumption for discontinuous processes (pitting)

Corrosion monitoring with EN: 3 identical WEs (scheme #2)

- corrosion of iron in 1M Na_2SO_4 (pH 3), RE = SSE + RE = iron



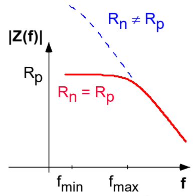


- noise due to hydrogen-bubble evolution
- $Z_{n,2}$ is not equal to √3 |Z| for each frequency because of the noise of the iron RE
- when possible, it is safer to work with a true RE

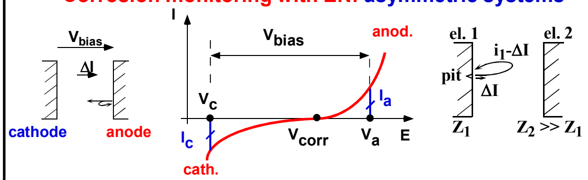
Corrosion monitoring with EN: noise resistance

$$R_n = \frac{\sigma_v}{\sigma_i} = \sqrt{\frac{\int_{f_{min}}^{f_{max}} \Psi_I(f)\,|Z(f)|^2\,df}{\int_{f_{min}}^{f_{max}} \Psi_I(f)\,df}}$$

- R_n depends on:
  - the frequency bandwidth analysed (f_{min}, f_{max})
  - the impedance Z(f) of the electrodes
  - the PSD of the current noise
- roughly:
  - when $|Z| = R_p$ for $f > f_{min}$ then: $R_n = R_p$
  - if not (coated electrodes, stainless steels…): $R_n \neq R_p$



Corrosion monitoring with EN: asymmetric systems

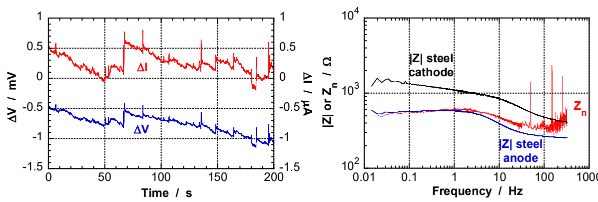


- same equivalent circuit with Z_a et Z_c instead of Z_1 et Z_2
- $$Z_n(f) = |Z_a(f)Z_c(f)|\sqrt{\frac{\Psi_{i_a}(f)+\Psi_{i_c}(f)}{|Z_a(f)|^2\Psi_{i_a}(f)+|Z_c(f)|^2\Psi_{i_c}(f)}}$$
- Z_n(f) and R_n depend:
  - on the impedance of each electrode Z_a et Z_c
  - on the noise level on each electrode Ψ_{i_a} et Ψ_{i_c}

➡ it is necessary to measure Z_a et Z_c for the noise analysis

Corrosion monitoring with EN: asymmetric systems

- 2 identical carbon steel electrodes (diameter 0.6 cm), RE = SCE, 0,1 M citric acid (pH = 2), V_{bias} = 350 mV, V_{anode} = -0.509 mV/SCE



- noise due to hydrogen-bubble evolution
- ΔI(t) and ΔV(t) show the processes (bubbles) on the **cathode!**
- Z_n gives the impedance of the **anode** at low frequency!

Preliminary conclusions

- electrochemical noise used essentially in corrosion
- the current noise allows discrimination between uniform and localised corrosion (weight loss, LPR, Z)
- with 2 WEs: measurement of both i(t) and v(t) ➡ Z_n et R_n
  - when $R_n = R_p$: estimation of i_{corr}
  - if not: corrosion monitoring with R_n
- impedance measurement with EN (no excitation signal)
  ➡ low-cost instrumentation
- common use: 2 identical WEs
  - the analysis of asymmetric systems is more difficult

Measurement of electrolyte resistance fluctuations

Measurement of electrolyte-resistance fluctuations

- between WE and RE
- between 2 identical electrodes

- purely ohmic quantity
- detect changes in the resistivity of the solution close to the electrode
- applications to two-phase systems: oil in water, gas-evolving electrode…

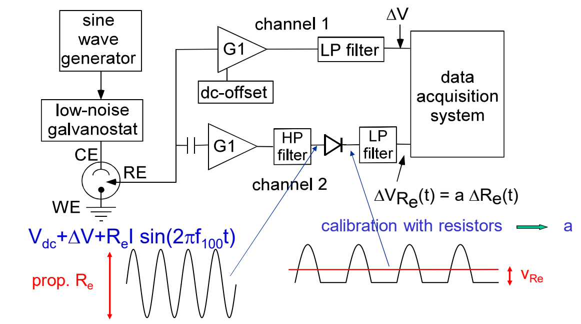
$V = E + R_e I$ ⟶ $\Delta V = \Delta E + \Delta R_e I$ if I is constant

simultaneously measured

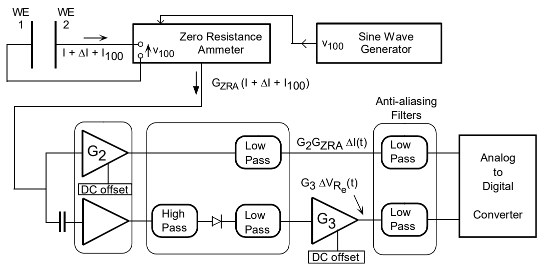
at I = 0: different information in ΔV and ΔR_e

Measurement of ΔV and ΔR_e

$V = E + R_e I$ at constant I ⟶ $\Delta V = \Delta E + \Delta R_e I$



Electrolyte Resistance Measurement (2 WEs + ZRA)

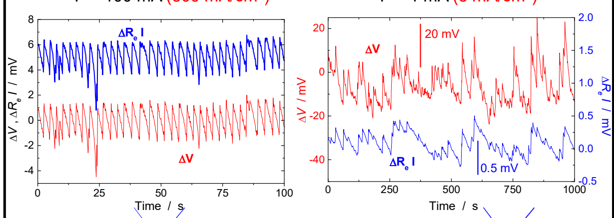


$$\Delta v_{R_e}(t) = b\,\Delta\left(\frac{1}{R_e(t)}\right) = -b\,\frac{\Delta R_e(t)}{<R_e>^2}$$

First example of ΔR_e measurements (one WE)

hydrogen evolution on Fe (ϕ = 5 mm) / 1 M H_2SO_4

I = -100 mA (500 mA/cm²) I = -1 mA (5 mA/cm²)



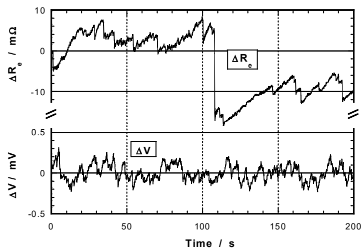
~~$\Delta V = \Delta E + \Delta R_e I$~~ $\Delta V = \Delta E +$ ~~$\Delta R_e I$~~

ΔR_e ⟶ ΔV ΔV not explained by ΔR_e

First example of ΔR_e measurements: one WE

hydrogen evolution on Fe (ϕ = 5 mm) / 1 M H_2SO_4

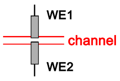
at corrosion potential: I = 0 ⟶ $\Delta V = \Delta E$

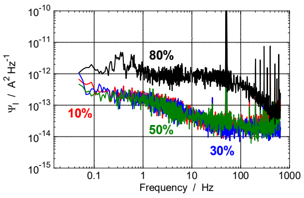


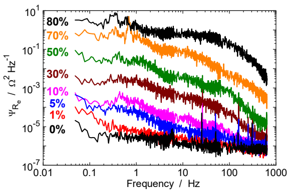
- ΔR_e and ΔV: complementary information
- ΔR_e ⟶ sensor of bubble evolution

Second example of ΔR_e measurements: 2 WE

- oil + 3% NaCl mixture in a flow-loop cell (v = 1.9 m/s)
- 2 iron disks (ϕ = 5 mm) connected with ZRA
- volumetric oil content: 0% < VOC < 80%







$\Psi_I(0)$ varies within only 1 decade for VOC ≤ 75%

$\Psi_{R_e}(0)$ varies within 6 decades for VOC between 0% and 80%

ΔR_e → sensor for monitoring o/b composition between 2 coupons

Conclusions

✓ EN used in corrosion
- detection of localized corrosion
- monitoring corrosion rate in the field (EIS in the lab)
- use EN in combination with other techniques: EIS, LPR…

✓ Be careful in measuring the noise
- possible to validate EN measurements
- necessary to test commercial equipments
- participate or organize Round-Robin tests

✓ Read good literature on EN for data interpretation

Further information

✓ Corrosion Testing Made Easy – Electrochemical Impedance and Noise, R. A. Cottis and S. Turgoose, NACE International, Houston, Texas, 1999; ISBN: 157590-093-9, 2000

✓ The interpretation of EN data, R. A Cottis, Corrosion, 27 (2001) 265

✓ Guideline for an assessment of electrochemical noise measurement devices, S. Ritter, F. Huet, R.A. Cottis, Materials and Corrosion, 63 (2012) 297

✓ Reliability of electrochemical noise measurements: Results of round-robin testing on electrochemical noise", R-W Bosch et al., Electrochimica Acta, 120 (2014) 379

← ECG-COMON (www.ecg-comon.org)

✓ The Electrochemical Noise Technique, F. Huet, Analytical Methods in Corrosion Science and Engineering, eds P. Marcus, F. Mansfeld, CRC Press, Series: Corrosion Technology, Volume 22, p. 507-570 (2006)

✓ Analysis of electrochemical noise by power spectral density applied to corrosion studies : MEM or FFT? U. Bertocci et al. J. Electrochem. Soc. 145 (1998) 2780

✓ Noise resistance applied to corrosion measurements: series of 6 papers, U. Bertocci, F. Huet et al., J. Electrochem. Soc. (1997 – 2002)

Thank you for your attention

if you want:

- a copy of the slides
- ask any question
- I test the EN measurements you performed with your commercial equipment
- participate to noise Round-Robin tests

→ email to francois.huet@upmc.fr

➢ C2018-11042: "Electrochemical Noise - Guidance for Improving Measurements and Data Analysis", F. Huet, K. Ngo (Monday, 9:10, room 228 A-B)

➢ C2018-11040: "Electrochemical Noise Measurements with Dummy Cells: Evaluation of a Round-Robin Test Series", F. Huet, S. Ritter (Wednesday, 9:25, room 131 A-B)