Primary Calibration of Acoustic Emission Sensors by the Method of Reciprocity- Industrial Exploitation of the Calibration bench

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Abstract. This article follows one published in the last Congress EWGAE 2012 (1). After a few reminders theoretical developments made, including the integration of the opening of a sensor function, we present in this paper the results of validation on a large number of sensors used in acoustic emission. We take the opportunity to also introduce our automated calibration bench capable of measuring the sensitivity of the sensors using different kinds of excitation mode surface, longitudinal and transverse. This bench is used for both the manufacturing control and periodic inspection of the sensors in our studies and daily benefits.

(1) Primary Calibration of Acoustic Emission Sensors by the Method of Reciprocity, Theorical and Experimental Considerations. Seydou DIA, Thomas MONNIER, Nathalie GODIN, Fan ZHANG

1. Reminder of the previous study results

1.1 Principle of the Method of Reciprocity

The quantitative analysis of the acoustic emission phenomenon requires prior knowledge of the sensitivity of the sensors used. We carried out various preliminary studies in order to identify the most appropriate method for determining sensor sensitivity: an absolute method that can be easily implemented. The method of reciprocity was selected as it allows absolute calibration and is relatively easy to implement.

The method of reciprocity stems from the principle of the same name according to which the transmission and reception sensitivities of a linear, reversible sensor are linked by a quantity H, known as the **reciprocity parameter** that is not influenced by the properties of the sensor. As a result, H only depends on the frequency, the medium and the type of propagating wave.

The transmission and reception sensitivities, respectively *S* and *M*, are defined by:

$$S = \frac{\omega_R}{I} \qquad \text{and} \qquad M = \frac{E_0}{\omega_{on}} \tag{0}$$

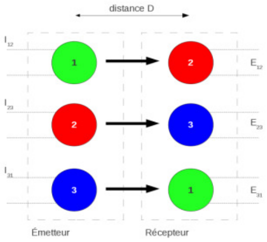
Where:

- ω_R is the component of the free-field propagation speed at a distance D from the transmitter;
- I is the current absorbed by the transmitter;
- E_0 is the open circuit voltage on the receiver terminals;
- ω_{on} is the normal component of the free-field wave propagation speed at the location of the receiver.

The reciprocity parameter H is defined by:

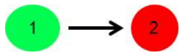
$$H(f) = \frac{M}{S} \tag{1}$$

Once we obtain the reciprocity parameter of the medium, we can then use the measurement of the currents (I) and voltages (E) to calculate the sensitivity of the sensors. There are two methods for doing this: a *full method* which requires 3 sensors and 6 measurements (I and E), or a *simplified method* with 2 sensors (a reference sensor and the sensor to be calibrated) and 2 measurements (I and E). Both methods are shown in Table 1.



Sensor	Transmission sensitivity S	Reception sensitivity M
C1	$\sqrt{H\frac{E_{012}E_{031}}{E_{023}}\frac{I_{23}}{I_{31}I_{12}}}$	$\sqrt{\frac{E_{012}E_{031}}{E_{023}}\frac{I_{23}}{I_{12}I_{31}}\frac{1}{H}}$
C2	$\sqrt{H\frac{E_{012}E_{023}}{E_{013}}\frac{I_{31}}{I_{23}I_{12}}}$	$\sqrt{\frac{E_{012}E_{023}}{E_{031}}\frac{I_{31}}{I_{12}I_{23}}\frac{1}{H}}$
C3	$\sqrt{H\frac{E_{013}E_{023}}{E_{012}}\frac{I_{12}}{I_{23}I_{31}}}$	$\sqrt{\frac{E_{031}E_{023}}{E_{012}}\frac{I_{21}}{I_{31}I_{23}}\frac{1}{H}}$

Full calibration (3 sensors calibrated simultaneously)



Sensor	Transmission sensitivity S	Reception sensitivity M
C2	$S_2 = M_2.H$	$M_2 = \frac{E_{012}}{I_{12}}.\frac{1}{S_1}$

Simplified calibration (1 reference sensor, 1 sensor to be calibrated)

Table 1: Principle of calibration using the method of reciprocity

1.2 Reciprocity parameter H

Table 2 gives the various expressions of the parameter H as a function of the excitation frequency, the propagation medium and the type of wave involved. In this table, f is the excitation frequency, E and σ are respectively the Young's modulus and the Poisson's ratio, and d is the distance between the transmitter and the receiver.

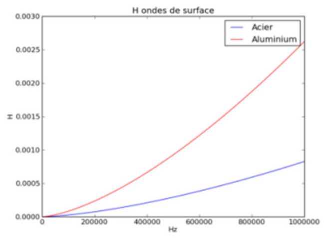
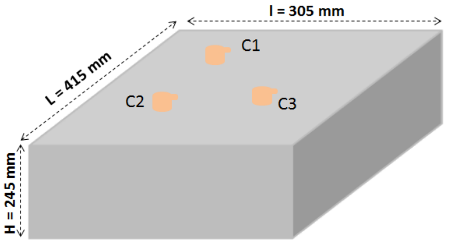
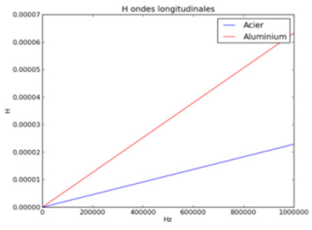
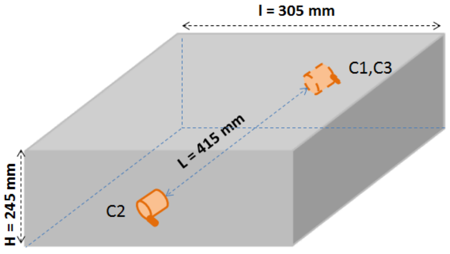
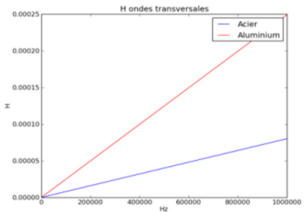
Mode	Formulation	Influence of the medium	Sensor arrangement
Rayleigh wave	$H(f) = 2\pi f \frac{1+\sigma}{E} kX\left(\frac{2}{\pi kD}\right)^{\frac{1}{2}}$		
Longitudinal wave	$H(f) = \frac{2f(1+\sigma)(1-2\sigma)}{dE(1-\sigma)}$		
Transverse wave	$H(f) = \frac{4f(1+\sigma)}{dE}$		

Table 2: Formulation of the reciprocity parameter H as a function of the type of wave and propagation medium (blue: steel; red: aluminium) in addition to the sensor arrangement on the steel block

1.3 Aperture effect of the sensor operating in Rayleigh mode

Bobber [2] has demonstrated the fulfilment of the reciprocity requirement in volume waves (longitudinal and transverse). In the case of Rayleigh waves, the sensor aperture effect renders possible the existence of frequencies for which there is no sensor response even if the sensor can transmit. Therefore the reciprocity becomes problematic in such a case. The aperture function of the sensor needs to be incorporated in the Table 1 equations in order to rectify this situation. This function is obtained by experimental measurement on a laser velocimetry bench and via specific processing software.

Figure 1 shows an example of this aperture function. In this figure, the aperture functions of a PAC µ80 sensor are calculated based on three methods: a uniform module and phase vibration method (piston method), a method with amplitude correction and a method with simultaneous amplitude and phase correction.

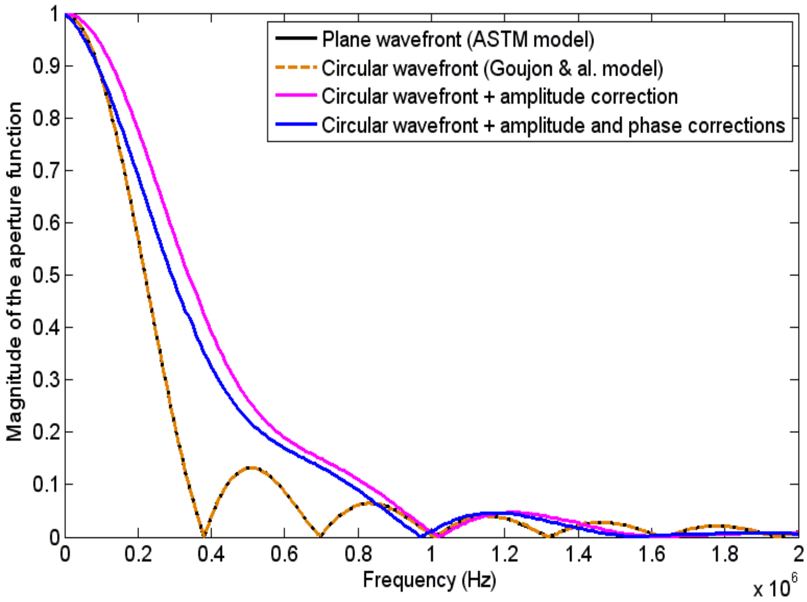


Figure 1: Comparison of the different aperture functions , including that proposed by Goujon et al. [3](orange) and the new model with amplitude and phase correction (blue and mauve curves)

Accordingly, a library of aperture functions was compiled featuring the most commonly used sensors on the market (Table 3).

Sensors	Resonance frequency [Use range] kHz	Frequency range (kHz)	Diameter * Height (mm)	Front face
Vallen SE 150-M	150	100-450	20.3*14,3	Ceramic
Vallen SE 45-H		20-450	20.3*22	Ceramic
Vallen SE 375-M	375	250-700	20.3*14,3	Ceramic
Vallen SE 9125-M			20,27*21,74	Ceramic
Vallen SE 900 MW	540	100-900	20,24*14,35	Ceramic
Vallen SE 1000-H	50	10-400	20,3*22	Ceramic
Vallen SE 1025-H			20,3*23	Ceramic
Vallen SE650	650	300-850	12,7*13,8	Ceramic
PAC R6	50 [90]	35-100	19*22	Ceramic
PAC R15	70 [150]	50-200	18*17	Ceramic
PAC R30	300 [350]	100-400	18*18	Ceramic
PAC R50	100 [500]	100-700	18*17	Ceramic
PAC R80	200 [800]	200-1000	18*17	Ceramic
PAC µ80	250 [350]	175-1000	10*12	Ceramic
PAC WD	125 [650]	100-1000	18*17	Ceramic
CETIM	180	50 - 200		ALU

Table 3: Aperture functions available in the library of the CETIM calibration bench

2. Presentation of the calibration bench

The calibration bench is comprised of the following components:

- A steel block with the following dimensions: 415x305x245 mm, i.e. 250 kg
- A voltage generator delivering a single pole-type excitation signal
- A current probe with the related conditioning to measure the current absorbed by the transmitter I
- A switching and conditioning unit to measure the voltage at the edge of the receiving sensor E
- A computer to control, acquire and process the signals
- A specific user interface

The operating principle of the bench is set out in Figure 2.

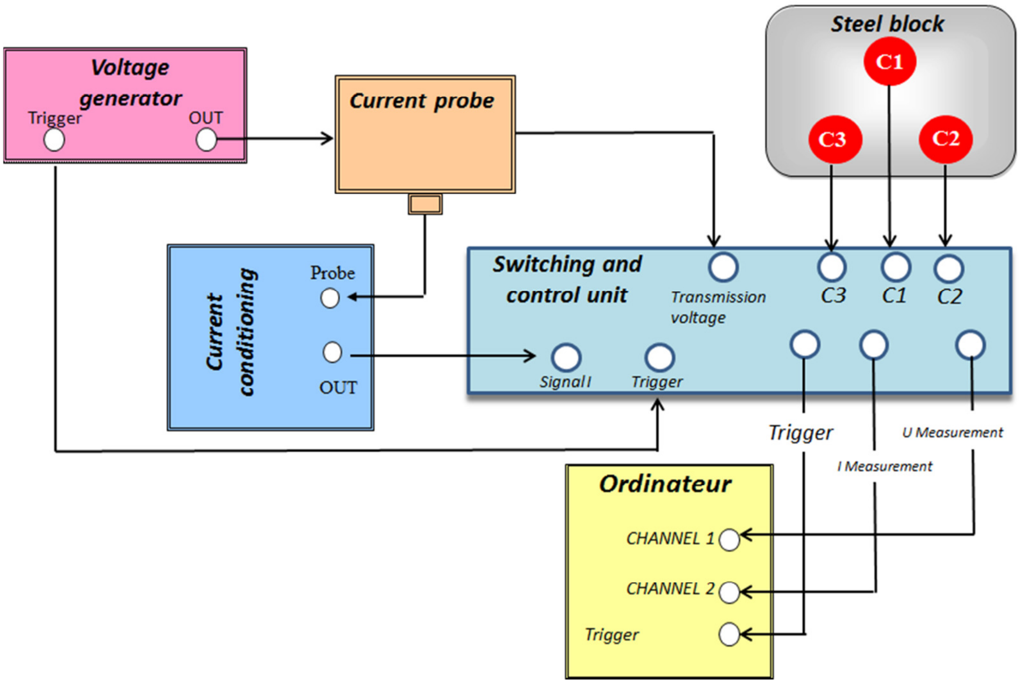


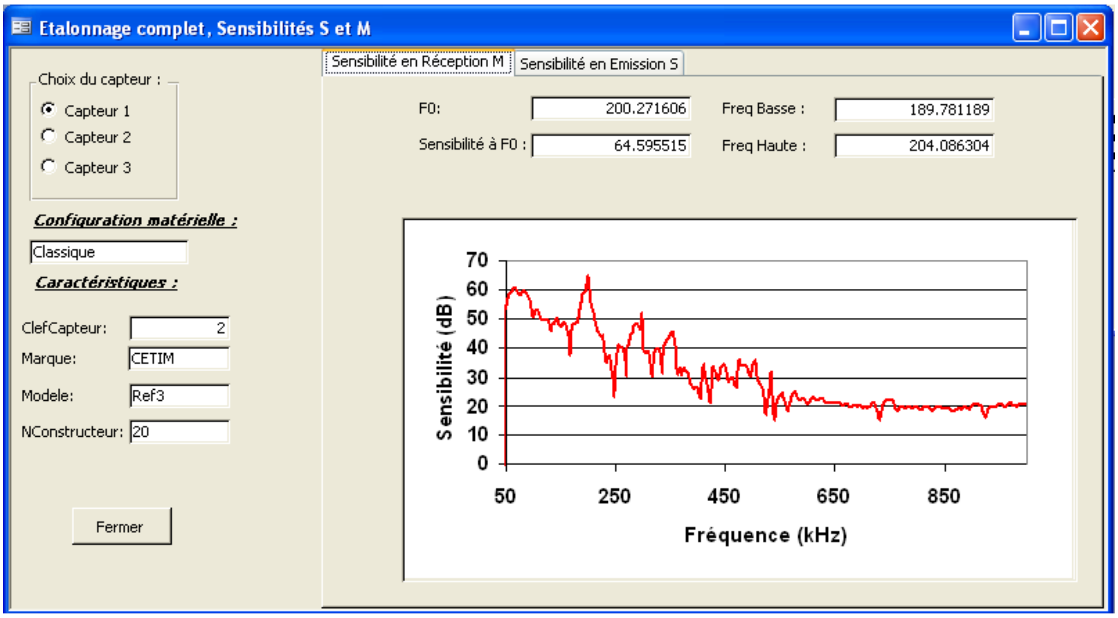
Figure 2: Block diagram of the acoustic emission sensor calibration bench

The operator can use the user interface to select the various calibration modes:

- Rayleigh mode with consideration of the sensor aperture function
- Longitudinal mode
- Transverse mode

For each mode, the operator can select between full calibration and simplified calibration. Full calibration does not last more than 5 minutes and simplified calibration lasts approximately one minute.

Figure 3 gives an example of a calibration result using the Rayleigh mode:



Choix du capteur :
● Capteur 1
○ Capteur 2
○ Capteur 3

Configuration matérielle : Classique

Caractéristiques :

ClefCapteur: 2
Marque: CETIM
Modele: Ref3
NConstructeur: 20

F0: 200.271606
Sensibilité à F0 : 64.595515
Freq Basse : 189.781189
Freq Haute : 204.086304

Figure 3: Example of the calibration result using the Rayleigh mode

Conclusions

The new bench implemented at CETIM allows absolute and full calibration of acoustic emission sensors with three wave types: Rayleigh, longitudinal and transverse. The fully automated instrument control and signal analysis help to meet all our requirements. These are notably optimising and managing our own sensor production, performing acceptance inspection and in-service monitoring of all sensors including those purchased on the market.

Reference list

[1] DIA S., Monnier T., Godin N., Zhang F., Primary Calibration of Acoustic Emission Sensors by the Method of Reciprocity, Theoretical and Experimental Considerations.

[2] Bobber, R. J., General reciprocity parameter. J. Acoust. Soc. Amer. 39 [1966], 680.

[3] Goujon L., Baboux J. C., Behaviour of acoustic emission sensors using broadband calibration techniques, Meas. Sci. Technol. 14 [2003] 903-908