Acoustic Emission Testing – Defining a new standard of acoustic emission testing for pressure vessels

Part 1: Quantitative and comparative performance analysis of zonal location and triangulation methods

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SUMMARY

For decades now, acoustic emission testing of pressure vessels has been used in France, Europe and the rest of the world. There are several regulatory texts, codes and standards worldwide which define the application rules of this method.
Since 2004, France has officially adopted a Best Practices Guideline [1] used as a reference for customers and service providers to apply this technology to various pressure vessels. According to the Guideline, like several other European (European standards) or American (Asme) texts, acoustic emission testing can be applied based on two techniques (zonal location method and pin-point location method (triangulation)). However, no comparative study of their performance, thus enabling their assessment, has been carried out.
By means of simple simulation calculations, this study highlights the significant differences in performance between these two techniques. The effects of other fundamental parameters, for example, acquisition threshold, are also quantified with respect to usage of acoustic emission.
This study may also be used as a basis for defining a new acoustic emission testing standard specifically and quantitatively defining the expected performance of a given configuration.
Today, the CETIM may apply this new testing methodology based on significant feedback enabling a greater reproducibility and sensitivity of Acoustic Emission testing.

INTRODUCTION

Acoustic Emission especially touches testing of pressure vessels. Indeed, it enables overall and rapid testing of large structures, significantly reducing maintenance time and shutdown of facilities. Methods have changed over the last decades, moving from very traditional and diversified methods to more standardised ones. However, some tests are still currently performed according to procedures which have more to do with the service provider's "reputation" rather than on a proven technique.
The authorities responsible for safety of facilities in France, requested "uniformisation" of acoustic emission testing methods for pressure vessels : this led to creation of the Best Practices Guideline (Guide des Bonnes Pratiques – GBP [1]), which has been officially adopted since 2004 and is used as reference for customers and service providers for application of this technology to various pressure vessels.
Several regulatory texts, codes and standards in other parts of the world define the general application rules of this technique: European or American (Asme) standards;
These texts, like GBP, authorise acoustic emission testing according to two techniques (zonal location and pin-point location (triangulation)). However, no comparative study of their performance, thus enabling their assessment, has been carried out. Lack of quantitative comparison leads to subjective assessment of performance concerning the techniques and the most cost effective, reputed "basic" solution is often selected. What is the real detection capacity of an acoustic emission source using these two methods? What is the coverage ratio of the tested structure? How can the testing level of two different structures be compared?

By means of simple simulation calculations, this study highlights the significant differences in performance between these two techniques. The effects of other fundamental parameters in the use of acoustic emission, for example, acquisition threshold, are also quantified.

A. Analysis of performance for the zonal location and triangulation methods, on a real case

A.1. Definition of the case studied – context

The performance for both techniques used will be compared based on real cases, dealt in accordance with the recommendations from the Best Practices Guideline (GBP) used as regulation in France. It should be noted that several other European or American texts are not much different from the GBP and lead to similar testing configurations.
A specific application case will be used to highlight this analysis. It represents several pressure vessels *as regards attenuation values*: it is a storage spherical tank with a 35 mm thick wall; this wall is painted and coated with heat insulating material.
The acoustic wave attenuation curve (frequency of the acoustic emission transducers is near 200 KHz) obtained from the Hsu-Nielsen source is shown in Figure No. 1.

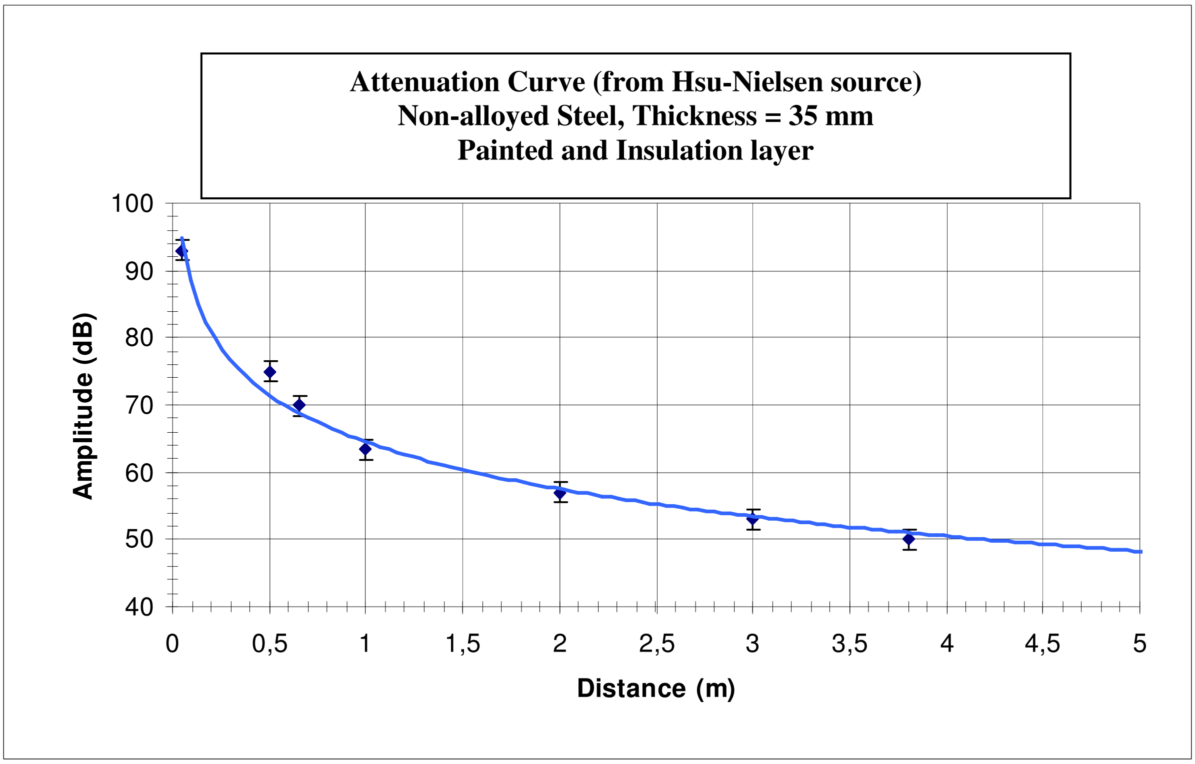


Figure No. 1: Attenuation curve obtained on 35 mm thick, non-alloyed steel, painted and covered with heat insulating material

Using the GBP recommendations as basis, the maximum allowed distances between sensors for this case are:

- for zonal location, the maximum authorised distance between sensors is 1.5 * [Distance at the assessment threshold = 50 dBea maximum], that is, in this case 1.5 * 4 m approximately that is to say 6 m.
- for triangulation, or planar location in this case, the maximum authorised distance between sensors of a single mesh, in the case of a maximum acquisition of 50 dBea, is equal to the distance to the acquisition threshold + 6 dB, that is approximately 2.5 m.

A very different number of sensors would therefore be needed for both testing configurations: a 10 m diameter spherical tank would require approximately 50 to 60 sensors in planar location against approximately 20 sensors for zonal location.
What is the detection performance of each of these configurations and how can this performance be quantified?

A.2. Performance analysis – Calculation of source-sensor distances

In order to assess both testing configurations, the detectability performance in each case is determined:

- for zonal location, by calculating the distance separating each point of the structure from the closest sensor,
- for planar location, by calculating the distance separating each point of the structure from the last sensor used for calculating the location (the 3rd sensor reached is used for these calculations).

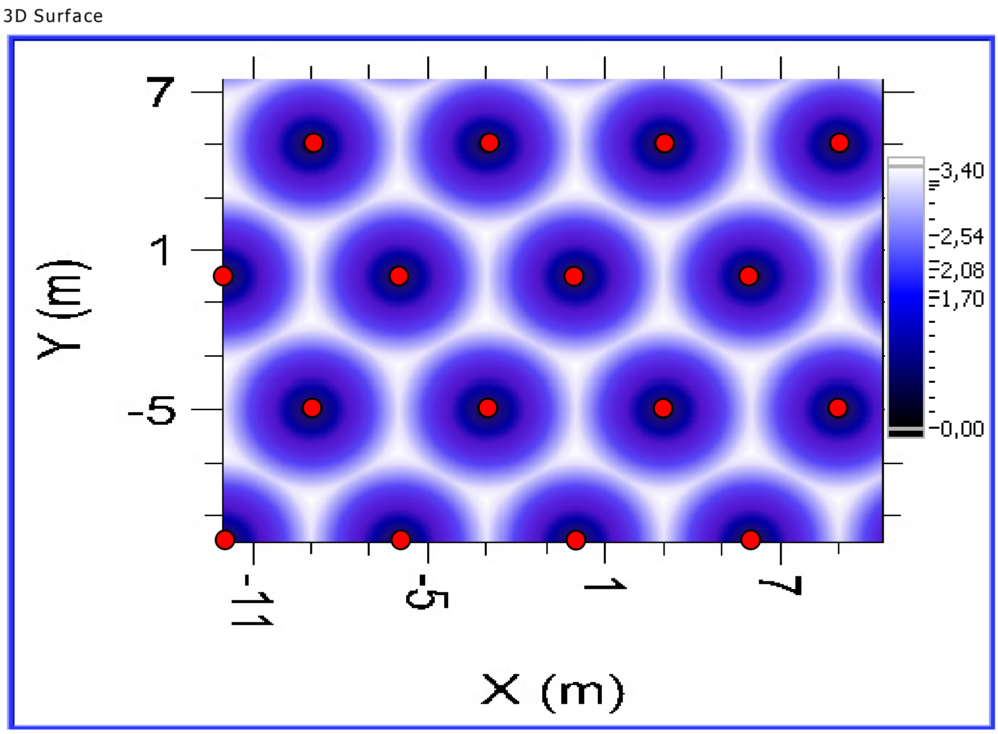


Figure No. 2a: Mapping representing the distance to the closest sensor, zonal testing configuration (in red, sensor position; maximum distance between sensors = 6.0 m)

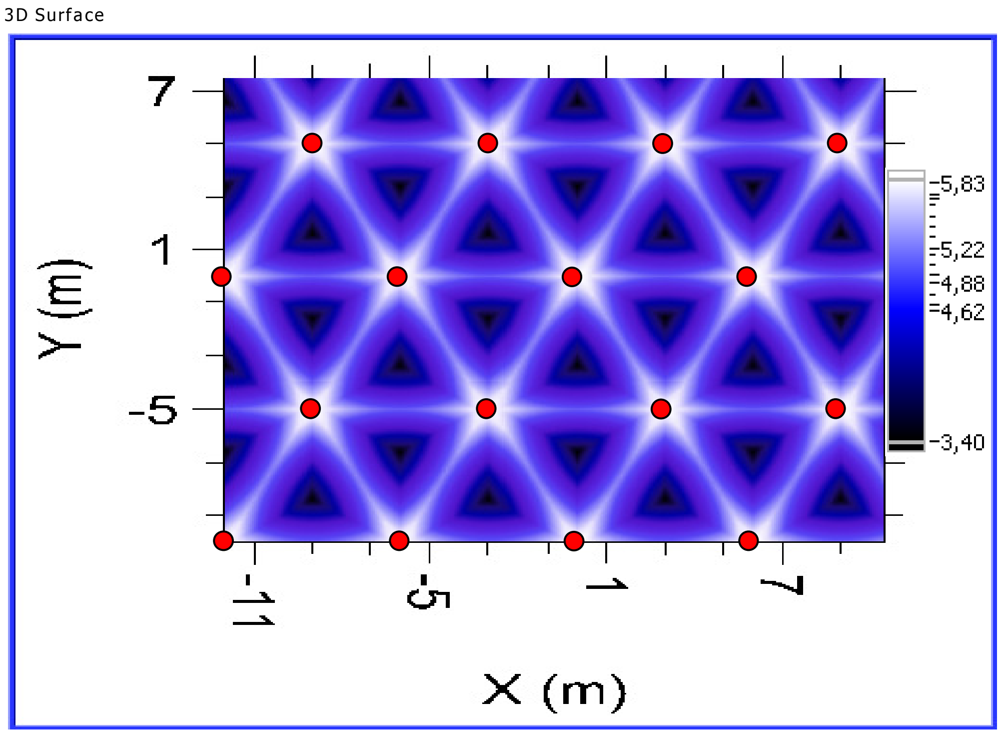


Figure No. 2b: Mapping representing the distance to the closest 3rd sensor, zonal testing configuration (in red, sensor position; maximum distance between sensors = 6.0 m)

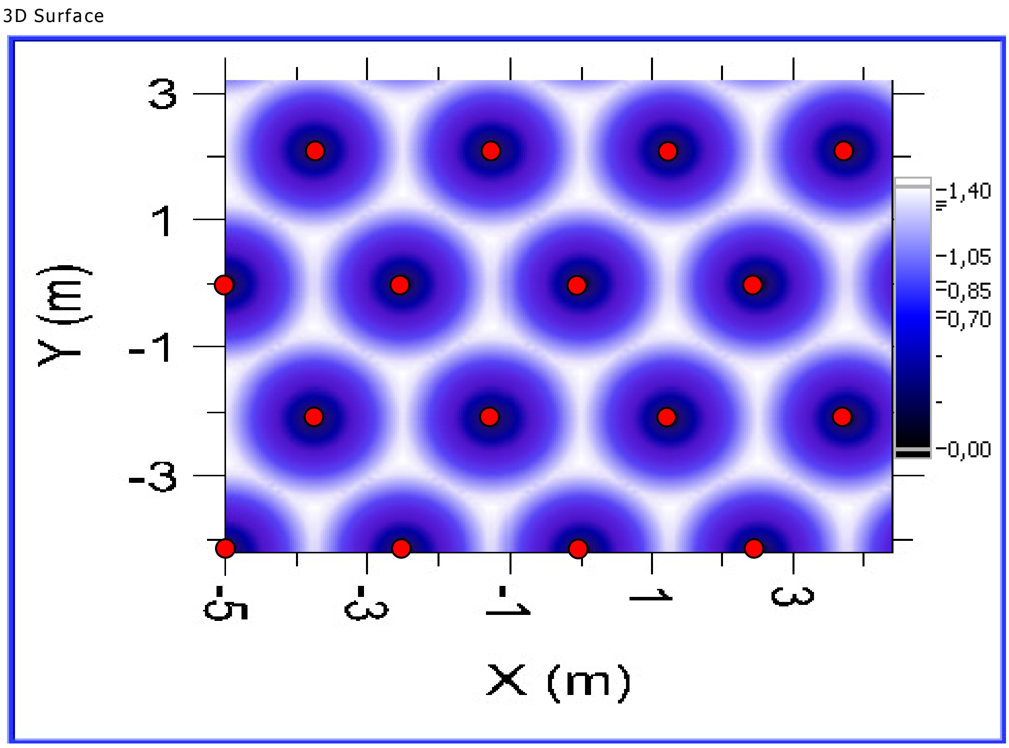


Figure No. 2c: Mapping representing the distance to the closest sensor, planar testing configuration (in red, sensor position; maximum distance between sensors = 2.5 m)

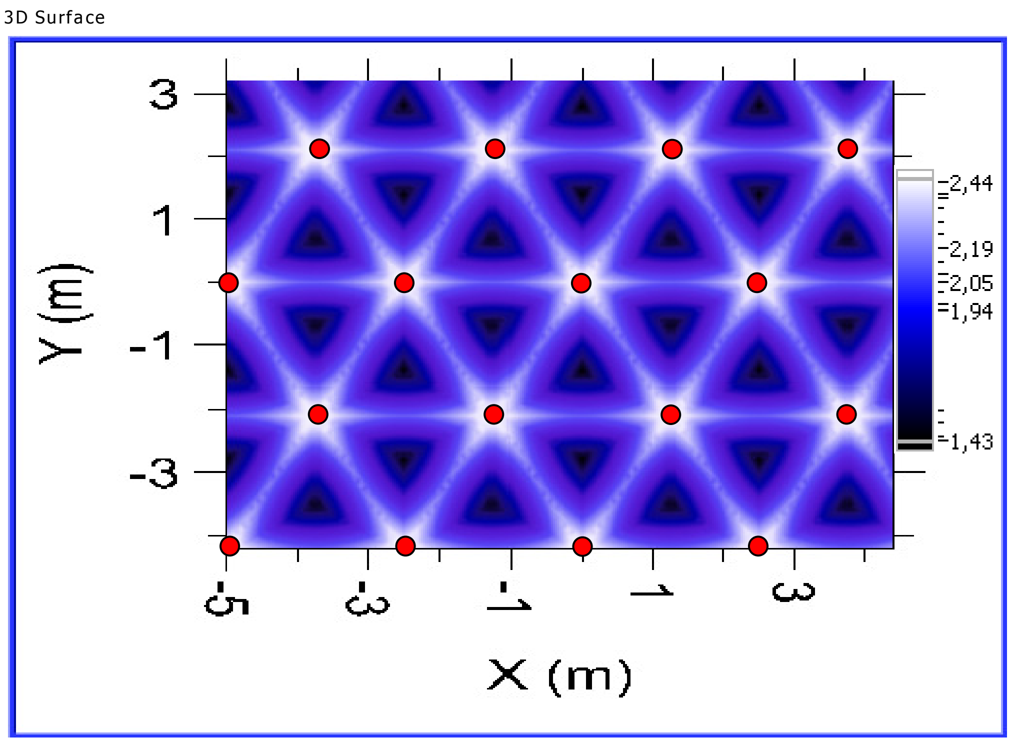


Figure No. 2d: Mapping representing the distance to the closest 3rd sensor, planar testing configuration (in red, sensor position; maximum distance between sensors = 2.5 m)

In conclusion, these various mappings show:

- For zonal testing configuration, (distance between sensors = 6.0 m), the point of the structure that is hardest to detect with the zonal location method is situated at 3.4 m. For the same configuration, planar location requires distances to the 3rd sensor reached between 3.4 m and 5.8 m.
- For planar testing configuration (distance between sensors = 2.5 m), the structure point that is hardest to detect with the zonal location method is situated at 1.4 m. For the same configuration, planar location requires distances to the 3rd sensor reached ranging between 1.45 m and 2.45 m.

A.3. Performance analysis – Calculation of minimum detectable amplitudes

We will later assess what the minimum amplitude of a detectable source is for each structure point for both location methods in order to better interpret these results and the performance differences which exist between these two testing configurations. The acquisition threshold must be taken into account in these calculations, as it defines the minimum measurable amplitude. In this case, the most unfavourable case authorised by the Best Practices Guideline is used, that is to say, a 50 dBea acquisition threshold. Figures 3a to 3d show these results:

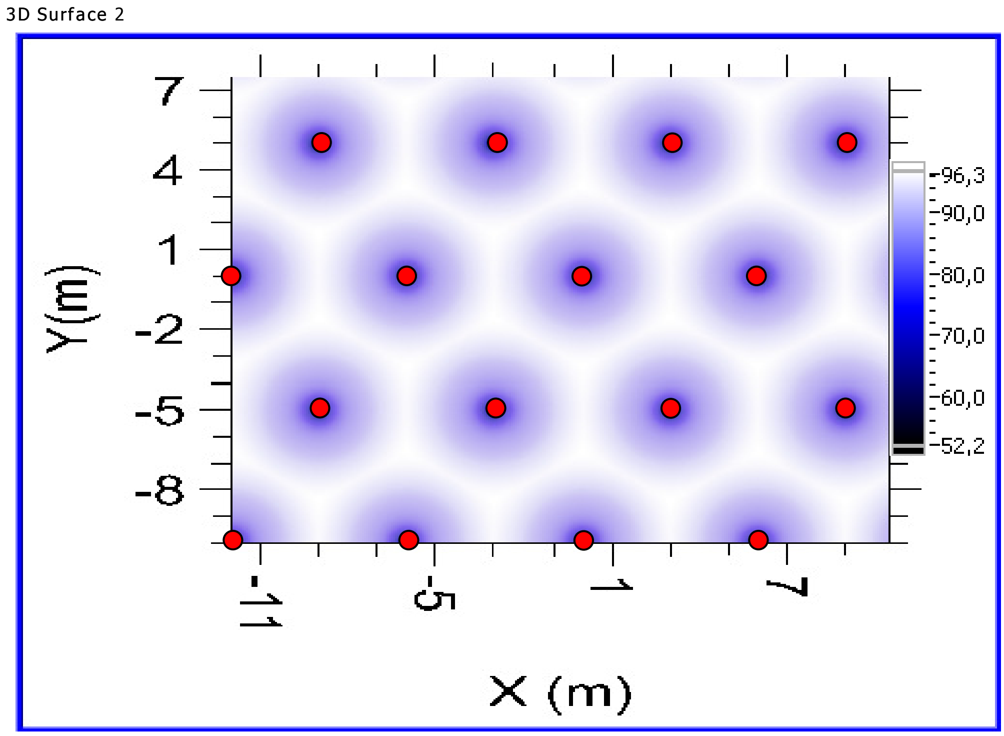


Figure No. 3a: Mapping representing the minimum amplitude that can be detected by zonal location, zonal testing configuration (in red, sensor position; maximum distance between sensors = 6.0 m)

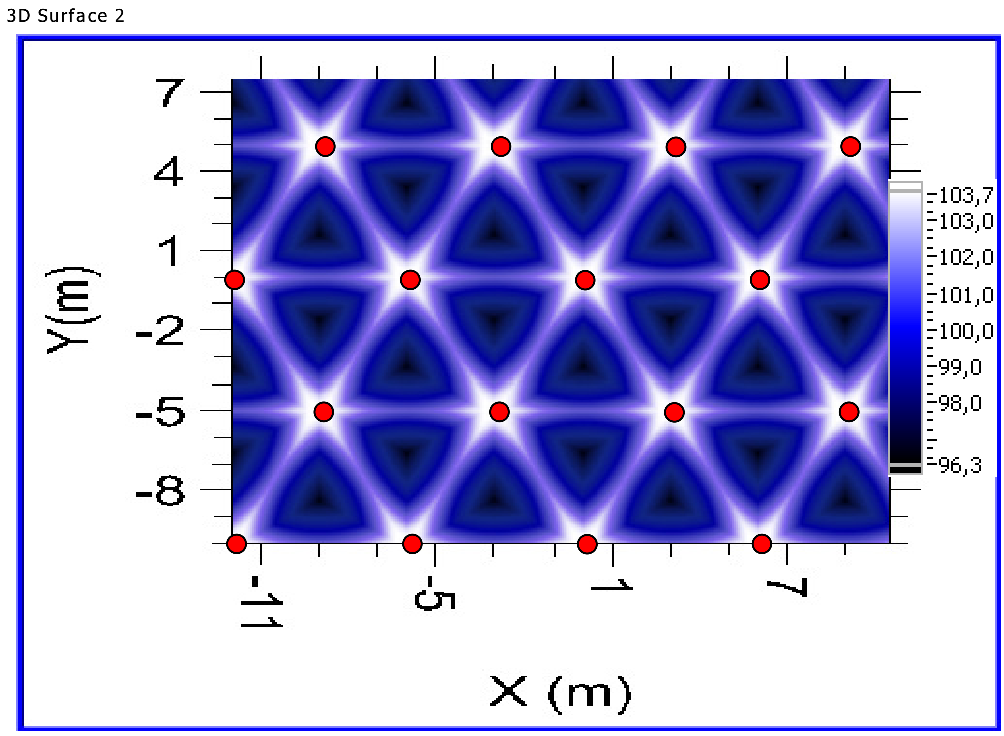


Figure No. 3b: Mapping representing the minimum amplitude that can be detected by planar location, zonal testing configuration (in red, sensor position; maximum distance between sensors = 6.0 m)

3D Surface 2

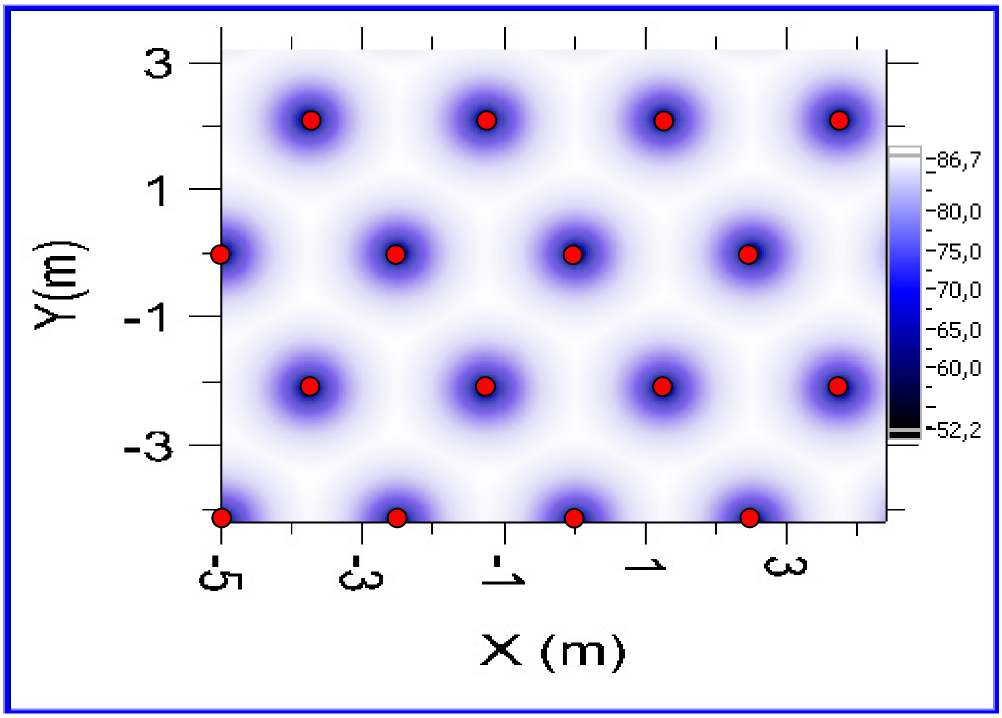


Figure No. 3c: Mapping representing the minimum amplitude that can be detected by zonal location, planar testing configuration (in red, sensor position; maximum distance between sensors = 2.5 m)

3D Surface 2

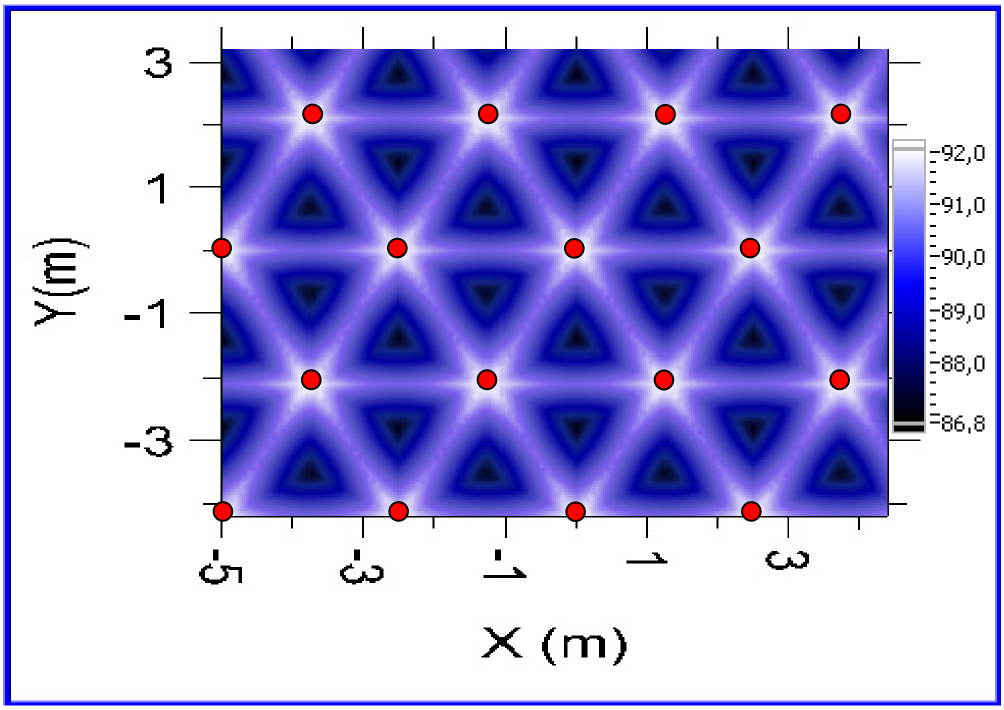


Figure No. 3d: Mapping representing the minimum amplitude that can be detected by planar location, planar testing configuration (in red, sensor position; maximum distance between sensors = 2.5 m)

Much information can be drawn from these mappings:

- Zonal testing configuration (6.0 m distance between sensors) enables detection of any acoustic emission source with equivalent source amplitude to that of a Hsu-Nielsen source (approximately 100 dBea initially – 98 dBea used in the modelling).
- However, this type of testing configuration only enables restricted application of planar location for this type of source (see Figure 3b). More specifically, planar location is only possible on 34 % of the surface (this surface corresponds to that for which the amplitude calculated is less than 98 dBea).

- Planar testing configuration (2.5 m distance between sensors) obviously enables detection of any acoustic emission source with equivalent source amplitude to that of a Hsu-Nielsen source with the zonal location method.
- This testing configuration also enables application of the planar location method on the entire surface (100 %, against 34 % for zonal testing configuration).

If only these considerations are taken into account, the performance differences are therefore relatively low. Indeed, the only difference between both configurations would simply be a loss of 66 % of the planar location surface. However, two significant parameters are not considered in this initial comparison: all real acoustic emission sources do not necessarily generate as much energy as a Hsu Nielsen source; furthermore, the measuring error, that it to say, assessment of its amplitude, carried out on the source is not quantified.

<u>A.4. Performance analysis – Consideration of variable amplitude acoustic emission sources</u>

Only the detectability of an acoustic emission source equivalent to a Hsu-Nielsen source (0.5 mm – 2H) was considered in the previous calculations.
It can be assumed that detectable acoustic emission sources in a real structure do not necessarily give off as much energy as a Hsu-Nielsen source. The detectability of a source, that is X dB less than a Hsu-Nielsen source, was therefore calculated for various source amplitude values. This detectability was moreover quantified in terms of detection ratio (for zonal location), and location ratio (for planar location).

Table No. 1 shows the performance for both types of testing configurations on detectability (zonal) and planar location. Analysis of this table, full of information, enables views for given amplitude of the detection and location capacity of both testing configurations. The following elements can also be re-iterated:

- Amplitude source that is **2 dB less** than the reference source:
  For the zonal testing configuration, we observe:
  - A 99 % detection capacity
  - A 0 % location capacity

  Whereas in the planar testing configuration, this same source can be:
  - 100 % detected
  - and located at 100 %
- For an amplitude source that is **10 dB less** than the reference source:
  For the zonal testing configuration, we observe:
  - A 31 % detection capacity
  - A 0 % location capacity.

  Whereas in the planar testing configuration, this same source can be:
  - 100 % detected
  - and located at 15 %.

The performance differences for both acoustic emission testing methods, which may be carried out in compliance with current texts, can therefore be quantified and qualified by this analysis. By highlighting performance differences, it becomes obvious that acoustic emission testing carried out with zonal location method is fundamentally different from testing with the planar location method in terms of sensitivity and information quality.

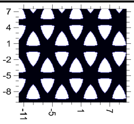
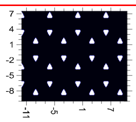
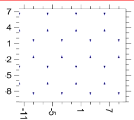
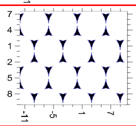
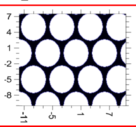
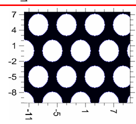
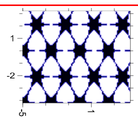
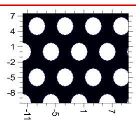
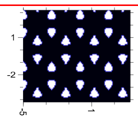
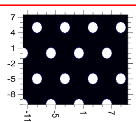
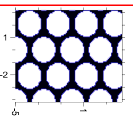
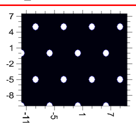
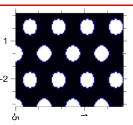
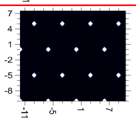
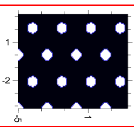
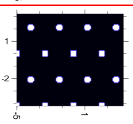
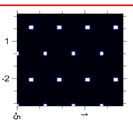
Amplitude de la source (dBea)	Configuration Zonale				Configuration Planaire			
	Localisation zonale		Localisation Planaire		Localisation zonale		Localisation Planaire	
	Taux de détection (%)	Cartographie	Taux de localisation (%)	Cartographie	Taux de détection (%)	Cartographie	Taux de localisation (%)	Cartographie
98 (source Hsu-Nielsen)	100		34		100		100	
97	100		6		100		100	
96	99		0		100		100	
95	93		0		100		100	
93	72		0		100		100	
90	47		0		100		73	
88	31		0		100		15	
85	11		0		65		0	
80	4		0		23		0	
75	2		0		11		0	
70					5		0	
65					2		0	

Table No 1: Performance differences between zonal and planar testing configurations depending on the amplitude of the acoustic emission source.
The mappings in white represent the regions that can be detected or located, and those in black, the regions that cannot be detected or located

Thus, if we consider for example that acoustic emission sources from the tested structure are included in an amplitude distribution centred on 85 dBea (amplitudes ranging between 55 and 115 dBea), for the zonal testing configuration we will note that:

- o 34.6 % of the sources can be detected
- o 10.6 % of the sources can be located,

Whereas in the planar testing configuration:

- o 59.0 % of the sources can be detected
- o 35.6 % of the sources can be located.

A.5. Performance analysis – Assessment of error on the observed amplitude

Detecting an acoustic emission source is the first step. However, what is the relevance of the information gathered by the operator? How does the operator view the intensity (or amplitude) of this source? We are here again going to rely on the modelling previously carried out to answer these two questions so as to obtain an estimation of these two factors.

The case of an amplitude distribution of acoustic emission sources centred on 85 dBea will therefore be used. We will assess the detection accuracy by calculating both factors:

- o The total percentage of "good" assessment. For example, a source measured at 75 dBea whereas its initial amplitude is 95 dBea will give an error of 21.1 %. The total percentage is the mean calculated on a given surface for a given amplitude distribution.
- o The mean error expressed in dB: This criterion is the mean of errors, expressed in dB, between the measured amplitude and the initial amplitude. Two values will be differentiated: the first incorporating errors on all acoustic emission sources, the second only incorporating errors on the detected sources.

The following results will therefore be obtained:

If, for example, we consider that the acoustic emission sources generated by the tested structure are comprised in an amplitude distribution centred on 85 dBea (amplitudes ranging between 55 and 115 dBea), for the zonal testing configuration we will note:

- o An overall detection accuracy of 20.9 %
- o An overall amplitude measurement error of 64.7 dBea.
- o An amplitude measurement error on the acoustic emission sources detected of 28.6 dBea.

Whereas in a planar testing configuration, we will obtain:

- o An overall detection accuracy of 39.3 %.
- o An overall amplitude measurement error of 48.9 dBea.
- o An amplitude measurement error on the acoustic emission sources detected of 26.1 dBea.

The difference between both configurations is clearly shown and can therefore be quantified using these different criteria.

Performance of both testing configurations for the case studied may be summarised as follows:

- o Zonal testing configuration:
- - 65.4 % of the sources are not detected
- - 34.6 % of the sources are detected, with a mean amplitude measurement error of 28.6 dBea
- - 10.6 % of the sources can be located (included in the detected 34.6 %)
- o Planar testing configuration:
- - 41.0 % of the sources are not detected
- - 59.0 % of the sources are detected, with a mean amplitude measurement error of 26.1 dBea
- - 35.6 % of the sources can be located (included in the detected 59.0 %).

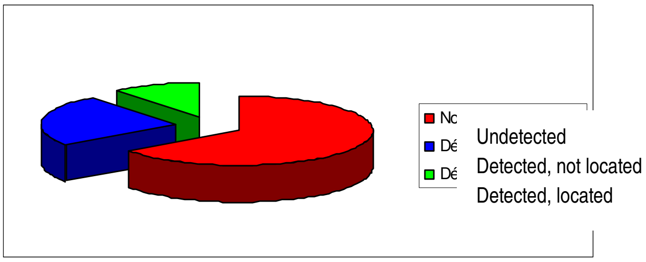


Figure No. 4a: Summary of performance for the zonal testing configuration

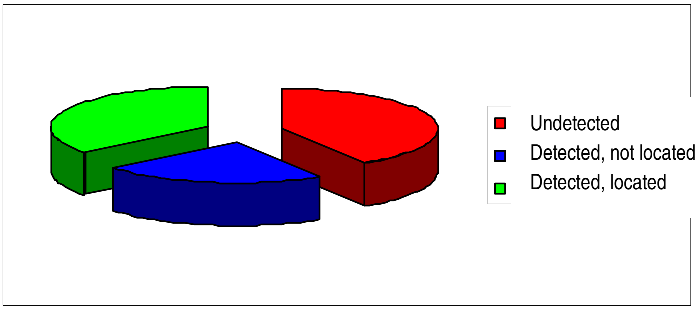


Figure No. 4b: Summary of performance for the planar testing configuration

A.6. Performance analysis – Consideration of information provided by planar location, enabling the correction of the measured amplitude

The current acoustic emission testing practices do not fully use information provided by planar location: indeed, the texts defining acceptability criteria, for example GBP in France, are restricted to giving the criteria based on the measured amplitude which, as was shown in the previous chapter, involves a 26 dBea error, on average (for the case studied).
If the information provided by planar location is used, that is to say the specific position of the acoustic emission source, the attenuation amplitude measured can be corrected and the real amplitude of the source can be estimated.
In this case, any acoustic emission source located will be measured without error (or less error). What are the overall performance gains of both testing configurations? By using the calculations carried out in Chapter A.4 (amplitude distribution centred on 85 dBea -amplitudes ranging between 55 and 115 dBea-), we therefore obtain:
For zonal testing configuration:

- An overall detection accuracy of 25 %
- An overall amplitude measurement error of 60.5 dBea,
- An amplitude measurement error on the acoustic emission sources detected of 26.5 dB.

Whereas in a planar testing configuration, we will obtain:

- An overall detection accuracy of 51.1 %
- An overall amplitude measurement error of 37.6 dBea.
- An amplitude measurement error on the acoustic emission sources detected of 14.7 dB.

It can be noted that using the information connected with location makes it possible to reduce the amplitude measurement error on the detecting acoustic emission sources:

- Zonal testing configuration: from 28.6 dBea to 26.5 dBea
- Planar testing configuration: from 26.1 dBea to 14.7 dBea

We can see that full use of the planar testing configuration makes it possible to obtain an information quality that is two times better than the zonal testing configuration with a lower measuring error.

B. Influence of testing parameters on detection performance

B.1. Influence of the acquisition threshold level

The acquisition threshold is a fundamental parameter influencing the results of an acoustic emission test. Indeed, this value sets the minimum detectable amplitude. The rules for determining this value are defined in the existing texts and standards and are based on the following two factors:

- The acquisition threshold value must be X dB above (for example 6 dB) the background noise, so that signals considered as non representative are not recorded,
- The acquisition value must be less than the "reference" amplitude value used to calculate the activity criteria for example.

Compliance with these two rules, in most cases, implies a certain freedom in choosing the acquisition threshold. Indeed, the most frequently encountered background noise conditions may make it possible to work with acquisition threshold levels less than the maximum authorised level. How does this impact detection of acoustic emission sources?
The effect of lowering the acquisition threshold will be quantified using the same case as that studied in previous chapters (where calculations were carried out with the maximum authorised threshold, that is to say 50 dBea).
Figures 5a and 5b summarise these results: it can be noted that the "performance" gain obtained by lowering the threshold from 50 to 40 dBea is significant as it enables:

- For the zonal testing configuration,
    - the undetected source ratio to be decreased from of 65.4 % to 33.2 %
    - the located source ratio to be increased from 10.6 % to 35 %
- For the planar testing configuration,
    - the undetected source ratio to be decreased from 41 % to 15.1 %
    - the located source ratio to be increased from 35.6 % to 70.6 %

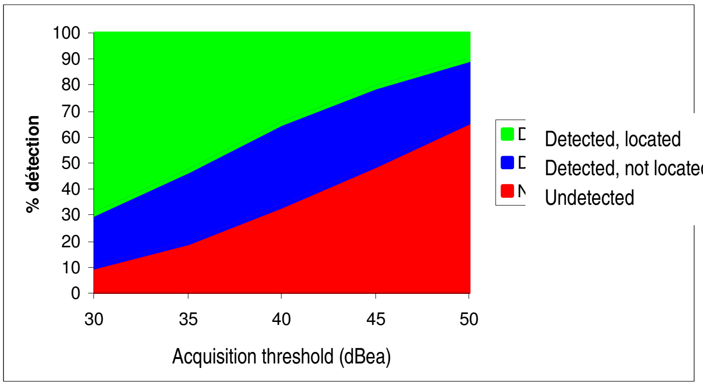


Figure No. 5a: Summary of performances of the zonal testing configuration depending on the acquisition threshold used

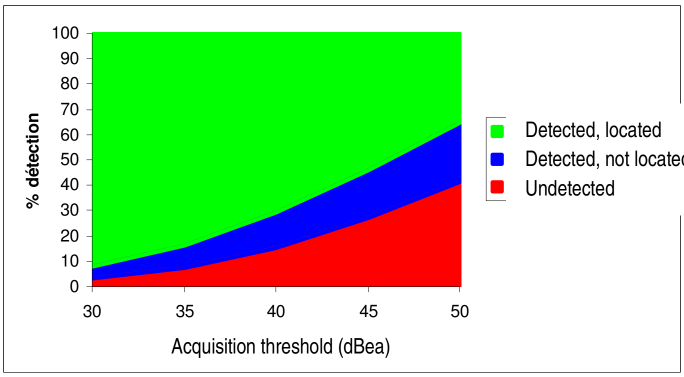


Figure No. 5b: Summary of performances for the planar testing configuration depending on the acquisition threshold used

B.2. Influence of the meshing type used

The meshing used in the tested structure is determined by several factors including the attenuation curve and the presence of specific structural elements. Some constraints (access for example) may also prevent installation of the sensors in specific areas of the structure.
The operator may have to use triangular, rectangular or other meshing depending on these elements. In order to evaluate the performance of the control, the influence of the meshing geometry on the quality of detection and location must be assessed and quantified.
Here, the differences between triangular and rectangular meshing for a given case will be highlighted. Figures 6a and 6b show the mapping differences (minimum detectable amplitude): note that the topography is different. Whereas in the case of a triangular mesh the most "critical" regions are those close to sensors, they are found in the middle of segments between sensors for rectangular meshing.

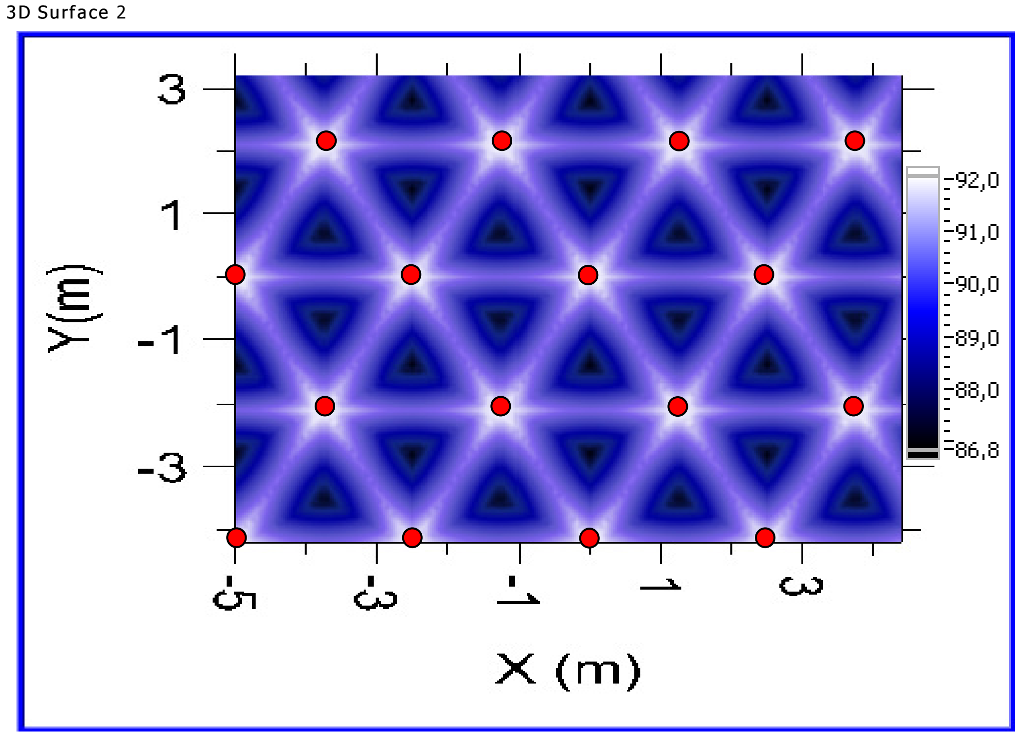


Figure No. 6a: Mapping representing the minimum amplitude that can be detected by planar location, planar testing configuration, triangular mesh (in red, sensor position; maximum distance between sensors = 2.5 m)

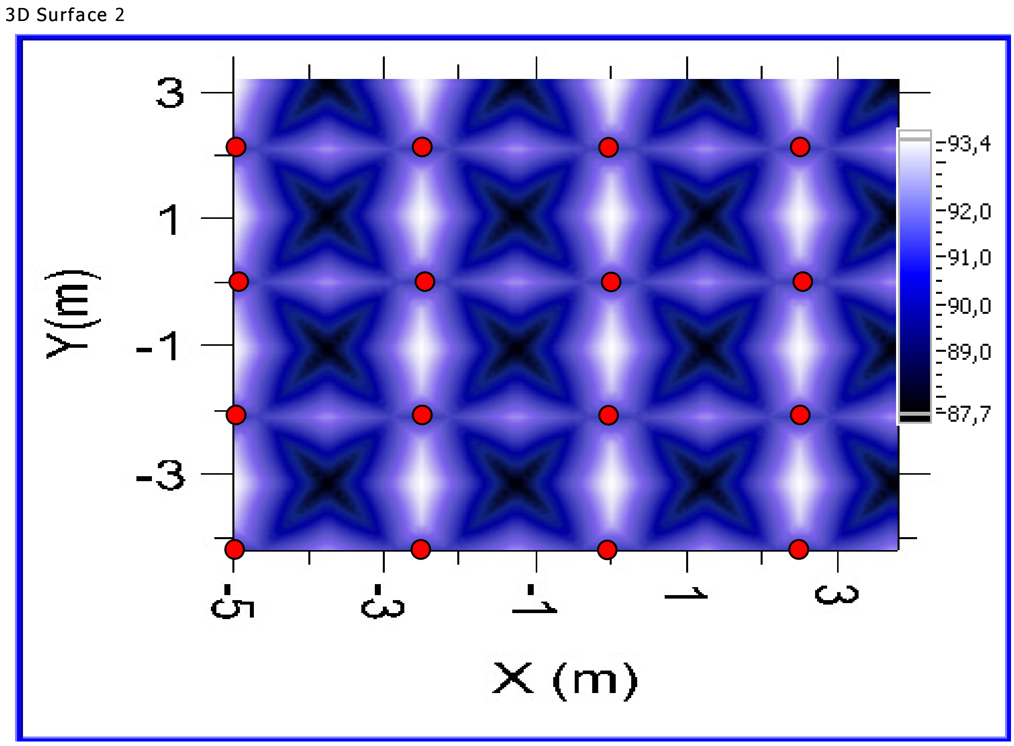


Figure No. 6b: Mapping representing the minimum amplitude that can be detected by planar location, planar testing configuration, rectangular mesh (in red, sensor position; maximum distance between sensors = 2.5 m)

B.3. Influence of the minimum number of sensors used in the location calculations

The meshing used in the tested structure (that is to say sensor coordinates) is not the only input data necessary for the location to be calculated. The number of sensors taken into account in the calculation is also an important factor influencing the result obtained as regards position and accuracy.
As a rule, location algorithms (planar location) use three sensors or more by default when the information on the fourth or nth sensor is available. The operator is able to filter calculations and can select only the calculation which used four sensors in order to obtain better location accuracy for example.
Increasing from three to four sensors minimum in the location calculation conditions significantly changes the results. The differences for a triangular meshing between location using at least 3 sensors and that using at least 4 sensors will be shown here. Figure 7 in comparison to Figure 6a shows the mapping differences (minimum detectable amplitudes): note that the topography is different as well as the values of the minimum detectable amplitude (difference recorded in this case from 2 to 3 dBea).
Using an additional sensor in the location calculation causes a loss of location capacity.

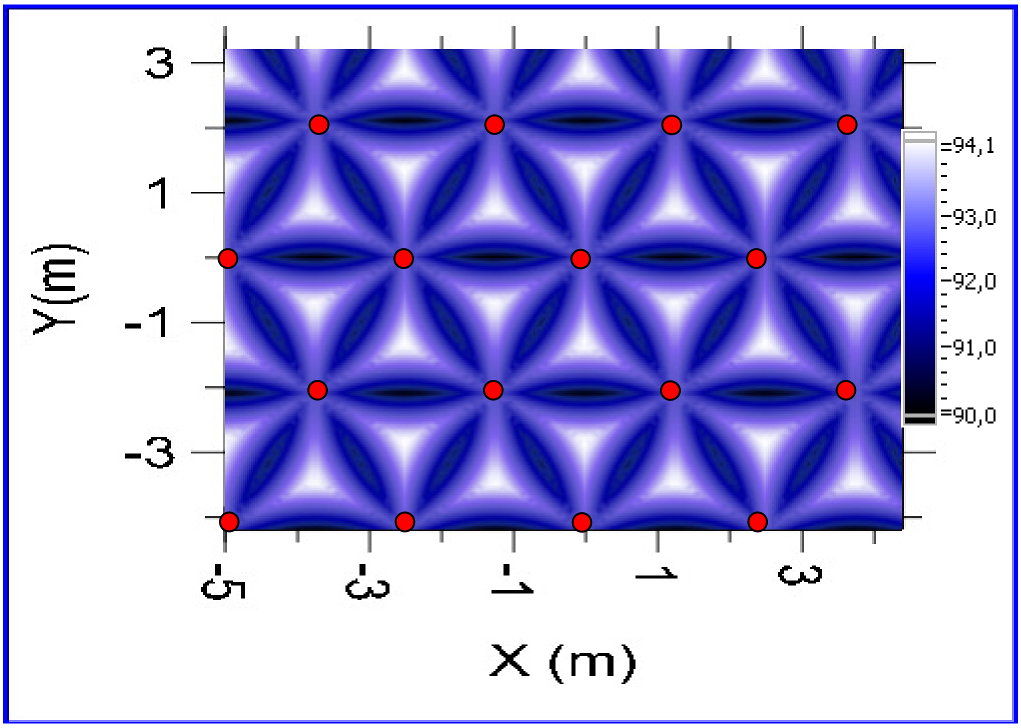


Figure No. 7: Mapping representing the minimum amplitude that can be detected by planar location, planar testing configuration, triangular mesh using at least 4 sensors (in red, sensor position; maximum distance between sensors = 2.5 m)
Using 4 sensors

C. Defining a new acoustic emission testing assessment methodology

C.1. Definition of an acoustic emission testing assessment methodology

The study carried out in the previous chapters illustrates that current acoustic emission testing practices defined and authorised by the various regulatory texts, codes and standards whether in France or elsewhere, may result in extremely varied performance levels. As a simple example, let us compare acoustic emission testing carried out in zonal configuration and with a 50 dBea acquisition threshold with testing carried out in planar location with a 40 dBea threshold (amplitude distribution of the sources centred on 85 dBea -amplitudes ranging between 55 and 115 dBea-):

- Zonal testing configuration, threshold = 50 dBea:
  - 65.4 % of the sources are not detected
  - 34.6 % of the sources are detected
  - 10.6 % of the sources are located (included in the 34.6 % detected)
- Planar testing configuration, threshold = 40 dBea:
  - 15.1 % of the sources are not detected
  - 84.9 % of the sources are detected
  - 70.6 % of the sources are located (included in the 84.9 % detected)

How can these significant sensitivity differences be taken into account given that there is no possible comparison between these two testing methods!

Based on the approach developed and described in this article, we propose that any acoustic emission testing should be "assessed" in terms of location performance expressed using simple and quantitative indicators. This performance calculation will be the same as that described in Paragraph A5, that is to say it will involve calculating the detection and location percentage for a population of acoustic emission sources, for example with amplitude centred on 85 dBea (ranging between 55 and 115 dBea). As in the previous example, it can be proven using both simple criteria that the first configuration (Zonal testing configuration, threshold = 50 dBea) is 5 to 7 times less efficient than the second testing configuration (Planar testing configuration, threshold = 40 dBea).

This assessment would enable:

- Firstly, quantitative comparison of acoustic emission testing performance. Instructing parties, users of this technique as well as organisation using testing results may take into account the level of testing quality and also request a minimum level of requirements, more specifically set by these criteria. Depending on the criticality of the tested vessel, a minimum level of requirements could be demanded.
- classification criteria to be adapted depending on the performance levels of the adopted testing configuration. Indeed, to date, no text, standard or code defines classification rules incorporating the testing "coverage ratio".

C.2. Changes and perspectives

The calculations performed in this study highlight that acoustic emission testing currently carried out is not well controlled and is therefore not used to its full potential. There is significant room for improvement for it to be more relevant and more accurate in its diagnosis. This study moreover shows that the following factors should be used today:

- amplitude correction: it was shown in the specific case developed, that use of amplitude correction enables the mean error as regards amplitude measurements of the detected sources to be decreased by half from 26.1 to 14.7 dBea. Furthermore, this amplitude correction reinforces the benefit of implementing and using the planar testing configuration to its full potential.
- Knowledge of the less monitored or located areas: this should enable the testing configuration to be better adapted to the structure. A "critical" region may be optimally tested by installing sensors so that they are located in the optimum meshing area.

CONCLUSIONS

Acoustic Emission (EA) is a unique, high potential testing technique as it enables quicker and less time consuming testing of large structures thus allowing operators to reduce the shutdown times for their facilities.
All regulatory texts, codes and standards which define the general application rules for this technique such as GBP in France, authorise use of EA according to two methods (zonal location and pin-point location (triangulation)). However, no comparative study of their performance, thus enabling their assessment, has been carried out.

From the study carried out using modelling calculations, we are able to determine that the performance differences authorised between these two techniques are significant and may reach a coefficient of 5 to 7, without being considered when analysing the information gathered, that is to say the results of the test. Furthermore, without this quantitative comparison, the "a minima" solution is often preferred by instructing parties as it is less costly and nevertheless recognised.

We propose that any acoustic emission test should be assessed on the basis of the approach developed in this study in terms of location performance by expressing this assessment through quantitative criteria such as detection and location percentage of a defined population of acoustic emission sources. These criteria, that is, the testing coverage ratio may be taken into account in analysing recorded information to obtain a more relevant diagnosis.

Finally, the results of this study show that use of a planar testing configuration must be preferred given that it allows the measuring error levels to be significantly decreased and therefore the impact of the error levels on the testing result, while enabling calculation of the source amplitude.

Backed by its experience, CETIM may now use these assessment tools and carry out well-controlled acoustic emission testing. Nevertheless, the professional guides, standards and codes should change so as to allow the industry to take advantage of the real potential of acoustic emission.

[1] Guide to good practice for AE testing of pressure equipment, 1st Edition, May 2004. AFIAP (French Association of Pressure Equipment Engineers). Edited by SADAVE. ISBN 2-906319-82-1