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MALICE
THE EFFICIENT ACOUSTIC IMAGING SYSTEM FOR PRECISE NOISE SOURCE LOCALIZATION

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ABSTRACT
Just as thermal imaging from Infra-Red radiation was soon revealed to be the most powerful way to improve thermal insulation packages of houses, machines, etc., by providing direct evidence of insulation weak points and thermal bridges, acoustical imaging techniques are now providing the most powerful diagnosis capability for improving the sound proofing of every mechanism or system - from household appliances to complete submarines...
However, acoustic waves widely differ from light or infrared, as they are very slow (340 m/s in air) and make things significantly more difficult. The intention of an acoustic software like MALICE is to make its use accessible to everybody with a minimum background in acoustic measurement. The aim of this paper is mainly to highlight the key aspects of these techniques, help understanding the differences from one to another, and help everybody facing a noise control challenge to decide if this technique may help him as much in the following examples do.

1. - INTRODUCTION
Aiming at a better understanding of noise measurements processing, the acoustical imaging software package MALICE allows a complete mapping of any tested unit. Indeed, this analysis tool is connected to an appropriate measurement system and performs specific processing finally delivering a fine representation of the acoustic sources distribution (including a unique focusing capability).
More explicitly, MALICE processes the nearfield measurements (performed with an array of microphones or hydrophones) in order to localize the noise radiating areas and to predict the farfield. The corresponding algorithms implemented in the software are based on a mathematical formulation now well established for acoustical holography in planar and cylindrical geometries [1].
An efficient application of this technique, regarding simplicity of both processing and experimental set-up installation is obtained with a plane wave formalism. This approach is implemented in the software standard version of MALICE.
The MALICE software allows the computation of the pressure field on a surface parallel to the measurement surface and in the immediate vicinity of the sources (backpropagation

processing). Then the subsequent computation of the pressure field away from the noise sources delivers radiated pressure maps (farfield prediction).
In all cases, the interpretation of the imaging process is straightforward. So the application of such a software significantly helps the user in his data reduction strategy. Compared to the complexity of the nearfield noise survey results, MALICE provides a direct guidance for vibroacoustic solutions engineering.
The application field offered by MALICE is rather large for both surface vessels (Navies) and equipments in various industrial activities (automotive and railway industries), and is the centre piece of a gas turbine health monitoring system (GASTEM).
Indeed MALICE software provides an acoustic "equivalent sources" approach of the whole machinery and introduces an adequate formalism to evaluate the efficiency of various "acoustic panels" to be implemented, where possible, in order to reduce the direct transmission, as well as the overall absorption, of the acoustic energy radiated by the considered system. Moreover, an acoustic panels design guidance module is directly connected to an extensive database of commercially available acoustic materials and can help elaborate multilayered solutions tailored to the application.
Typical examples of obtained results will illustrate the capabilities and efficiency of the software.

2. - NOISE SOURCES, NEARFIELD AND ACOUSTIC CONFINEMENT

Vibroacoustic physics is based on relatively simple phenomena (the capability of some particular dynamic disturbances of travelling nearly unattenuated in a fluid/solid medium, i.e. a wave propagation like light, electromagnetic waves or heat), but the practical interactions with human made objects are, in fact, rather more complex:

- as the vibroacoustic waves are very slow (from 10 m/s up to 6000 m/s), the wavelengths at audible frequencies (10 Hz - 14 kHz) are ranging in size as the objects of interest (a machine, a car, a house, ...), i.e. from several centimeters up to hundreds of meters. This means that an object is never big enough to make the propagation simple. On the contrary, boundary reflections, propagation disturbances and local effects generally predominate. Similarly, diffraction predominates over direct paths, few "acoustic bridges" are sufficient to jeopardize the most efficient insulating materials, small apertures make sound proofed casings ineffective, etc.
- this can be summarized as a predominant role of boundary conditions, i.e. what modelling people never exactly know, and explains the omnipresence of resonances with huge amplification factors as compared to the 2 basic terms of kinetic energy (a dynamic force F applied to a rigid mass M generates an oscillating acceleration $g = F/M$) and deformation energy (a dynamic force F applied to a compliant elastic body of stiffness K producing an oscillating displacement $x = F/K$). This perpetual exchange between kinetic and deformation energies is the most fundamental aspect in vibroacoustics and remains the best guideline to interpret even the most complex modeshapes and vibroacoustic patterns. This also explains the popularity of mass-spring schematizations!
- when we are looking at the noise emission of a vibrating body with a microphone (hydrophone underwater), another issue is that we are never far from it (here again in terms of many wavelengths). This means that the natural selection between the sound itself (= what can propagate nearly unattenuated very far away, i.e. the singular solution of the sound equation) and the local flow induced by the vibrating surfaces in the surrounding fluid. Acousticians define as *nearfield* the volume surrounding the object where these non-acoustic (so called evanescent) oscillations of the fluid are recorded in addition to the sound *stricto sensu* by the microphone.
- the hard point is to determine the real extension of the nearfield, as it depends on :

- the frequency
- the ratio of flexural waves of the object over the sound speed
- the extension of the "source" on the object, i.e. the domain where vibrations are correlated.

As a consequence, you never know in advance how extended the nearfield is when you undertake acoustic surveys...

- the last consequence of this low sound and vibration waves velocity is that the volume where you listen to something is never big enough in itself... What we call *acoustic confinement*. Reflected waves come from any wall, floor, sea surface, seabed, measurement device, nearby equipments, etc., and generate additional interferences. Sometimes, you have even to take them into account as modifying the vibroacoustic field on the source itself ! Most of the time, hopefully, you can assure that the source behaves as in a fully open medium, but you record anyway a well distributed sound field.

Acoustic rooms are built with considerable care (and cost !) to avoid wall reflections (anechoic rooms), but they are anyway limited in their frequency range and require the tested object to be an easily movable sound source... Another class of such rooms are built with very reflexive walls (polished concrete, hard tiling, ...) to maximize the acoustic confinement up to a totally, reverberant situation. In such cases, a single microphone is sufficient to estimate the whole sound power radiated by the measured source. But here again, some limitations occur... Real life situations are always in-between. Close enough to the source, echoes or peripheral disturbing noise makers may be neglected, but you remain in the nearfield. At larger distances, the challenge becomes to manage with the confinement induced perturbations.

The acoustical imaging system MALICE presented hereafter is aimed at solving these 2 issues and reflects some 15 years of experience in industrial acoustic surveys. Indeed, MALICE provides acousticians and non-acousticians with capabilities of :

- measuring the effective noise levels in such imperfect conditions as those mentioned above,
- identifying the predominant noise sources,
- data reduction for further modelling ,
- evaluating noise control solutions packages.

This system not only provides global sound pressure or sound power levels or spectra, but also 2- or 3-dimensional directivity patterns and a clear picture of the sound radiating "hot spots" where actions are required to reduce noise emissions. These hot spots reveal most of the time unwanted/unexpected noise paths internally to the system, transferring the energy from the primary sources (e.g. a shaft unbalance, a combustion mechanism in a motor engine, ...) to the surrounding acoustic medium.

3. - ACOUSTIC MEASUREMENT TECHNIQUES

The aim of this section is simply to briefly recall the main features of currently available measurement techniques in acoustics, as well as their respective advantages and limitations.

- the microphone (hydrophone underwater) provides the simplest of such devices when it is used as a unique sensor. When located relatively far away from the radiating object in free field conditions (or in an anechoic room), it helps establish directivity patterns among others. Applied in totally reverberating conditions, it delivers the total radiated acoustic power,
- an intensity probe (which consists of a couple of phase matched microphones) allows for the separation of evanescent waves (i.e. reactive intensity, characterized with vanishing time domain average) and propagative components (active intensity, i.e. real sound : $p = \rho c v$). Using such probes in the very nearfield of the radiating object may cause some

trouble because of poor signal to noise ratio due to the evanescent waves, which make the identification of acoustical components more difficult.
One drawback of intensity techniques is some difficulty reading the produced 3-dimensional vector fields (many closed lines, ...), especially in the case of extended or multiple correlated sources,
- an acoustic antenna (a real or a synthetic one, provided phase reference is available in the latter case), will deliver nearfield pressure maps all around the radiating object. Nevertheless, such a representation suffers again from the interferences induced by evanescent components, which often make the obtained result somewhat puzzling !

The introduction of adequate processings of pressure measurement obtained in the nearfield, as they are implemented in MALICE, makes available the ultimate result in acoustical imaging by :
- operating a space Fourier transform of the measured nearfield pressure map at each frequency,
- selecting in such a wavenumber representation those components which relate to effective sound radiation (propagative components)
- possibly adding some non-propagative components (evanescent waves) for an improved resolution in source location and contour identification (indeed insuring physical unicity of the final obtained solution),
- defining a plane wave decomposition (taking into account with phase references) of this field in the wavenumber representation
- applying a retropropagation technique, which makes interferences between all the different plane wave components disappear and produces a picture of the elementary sources responsible for the noise generated, even in case of fully correlated sources.

Extrapolation in the farfield of the propagative components finally delivers directivity patterns and access to the radiated power.
Notice that additional functions provide MALICE's user with the necessary tools for practical handling of possible missing points in the measurement meshing (unreachable measurement points, local defect on a microphone, ...). A more detailed presentation of the used extrapolation techniques is given in the joint paper on SALSA, a variant system from MALICE.
As a final comment, it is to be emphasized that access to 3-dimensional acoustical holography will be provided by coupling MALICE with advanced vibroacoustic numerical codes such as ASTRYD. Then the sometimes impracticable requirement for a planar acquisition geometry will be relaxed, thus offering an even wider field of investigation to the operator !

4. - APPLICATION EXAMPLES

The application field offered by MALICE is rather large, ranging from both surface vessels and submarines noise inspection and qualification (Navies) to fine scanning of noisy equipments in various industrial activities (automotive and railway industries). It is a centre piece of a gas turbine health monitoring system as well. An extensive presentation of the complete set of applications faced with MALICE up to now is not the aim of this section. We simply selected a couple of examples illustrating the multiplicity of its possible applications in various industrial fields.
Notice that some specialized features related to its use in the automotive industry are given in a joint paper presented at the conference (see ref. [2]).

4.1 - MALICE as an essential component of a health monitoring system for gas turbine

As a first example, we focus on a system dedicated to health checking for a gas turbine. The integration of several monitoring techniques has resulted in VA-GASTEM, a system that can

produce an almost instant indication of the health of an industrial gas turbine and faults that are developing within the engine.
The innovative aspect of this development was to combine an acoustic approach, based on MALICE acoustic holography, with thermodynamic techniques. Data fusion of the readings from the different techniques allows faults to be pinpointed through a mutual learning process, thus providing the operator with the essential information (almost real time through successive improvement of the system) regarding the detection of the onset of faults that could lead to expensive downtime and repairs.
Figure 1 gives a partial illustration of the system on site. Particularly, we see the 2 antennas dedicated to acoustic signals collecting : a low frequency array of microphones for sound in the 100 Hz to 3.5 kHz range and a high frequency array for signal up to 17 kHz. The conjunction of both arrays improves directivity assessment. Applying the retropropagation techniques implemented in MALICE allows such arrays to be some distance from the hot and dirty atmosphere around the turbine, therefore reducing background noise and producing a high signal to noise ratio for easier analysis. As an outcome from the analysis conducted by VA-GASTEM, backpropagated fields are given on Figure 2, where the emergence of typical features characterizing (artificial) blade default appear clearly.

4.2 - MALICE as a tool for ship radiated noise measurements
In the context of extensive studies of the acoustic qualification of surface vessels as well as submarines, it is particularly interesting to emphasize experiments conducted on typical naval systems, which previously required the use of a specific noise range in the Mediterranean. The availability of MALICE makes it possible for the French and Italian Navies to perform the different radiated noise measurements in their own dockyard basin, taking into account the effects of confinement and shallow water conditions.
The way to proceed to such qualification campaigns is illustrated on Figure 3.
The outcome is that the regular calibration of submarines is no longer required by the Italian Navy, which results in significant maintenance cost savings, a better control of the onboard noise sources and a self-reliance of the fleet. Moreover, the French DCN currently uses this software in order to characterize noise source distribution on their ships and submarines.

4.3 - MALICE in the automotive industry
Some of the automotive industry applications of MALICE presented hereafter are detailed in the joint paper on SALSA [2], a specialized system allowing for embarked measurements in a passenger car, aiming at car opening quality assessment. This system leads to an efficient identification of possible weak points on the vehicle such as : wiper blade noise annoyance at high car speed or possible door lock defect identified through a very localized signature, if we restrict that presentation to some of the most typical features of SALSA (see Figures 4 and 5 hereafter).
Also the extensive acoustic analysis of Defence armoured tracked vehicle has been recently conducted with MALICE. Figure 6 shows typical results obtained in that context. Here again, the source localization capabilities of the software are evident and help conducting a noise reduction strategy for such classes of noise problems.
Note that apart from its diagnosis capability, MALICE also includes a purely predictive module, where the engineer is allowed to evaluate the impact of different sources locations on their subsequent radiated pressure directivity for example. By the way, it introduces an adequate formalism to evaluate the efficiency of various "acoustic panels" to be implemented where possible, in order to reduce the direct transmission as well as the overall absorption of the acoustic energy radiated by the considered system. Moreover, an acoustic panels design

guidance module is directly connected to an extensive database of commercially available acoustic materials and can help elaborating multilayered solutions tailored to the application.

5. - CONCLUSIONS

After a thorough recall of the principles which sustain MALICE as well as on the specific features of the system, we presented some typical examples excerpt from its various application fields.

One of the advantages of the tools implemented in MALICE is their integration in an overall systems approach to noise reduction methodology. In this systems context, MALICE software provides an acoustic "equivalent sources" approach of the whole structure measured. As well MALICE introduces an adequate formalism to evaluate the efficiency of various "acoustic panels". Thus selective and partial implementation is possible, so as to reduce the direct transmission as well as the overall absorption. Moreover, an acoustic panels design guidance module is directly connected to an extensive database of commercially available acoustic materials and can help elaborating multi layered solutions tailored to the application.

Hence MALICE is a critical component of acoustic signature analysis of various industrial systems, because it is the experimental tool that guarantees the opportunity of proper evaluation and monitoring the acoustic signature from the noise and vibration monitoring of critical system components.

MALICE runs on a compact VXI PC. Together with the associated SALSA and ASTRYD systems, MALICE is now actively marketed in Australia and the Asia-Pacific region through Pacific Noise and Vibration, an Australian company based in Canberra

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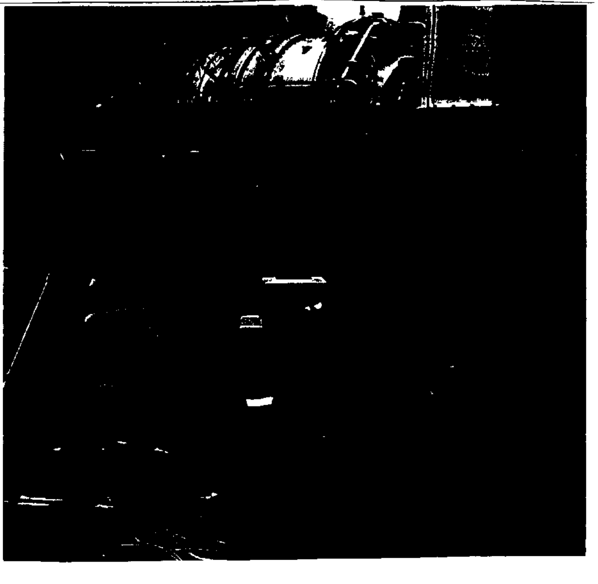

Figure 1:
Gas turbine health
Monitoring system
Measurement arrays
On site

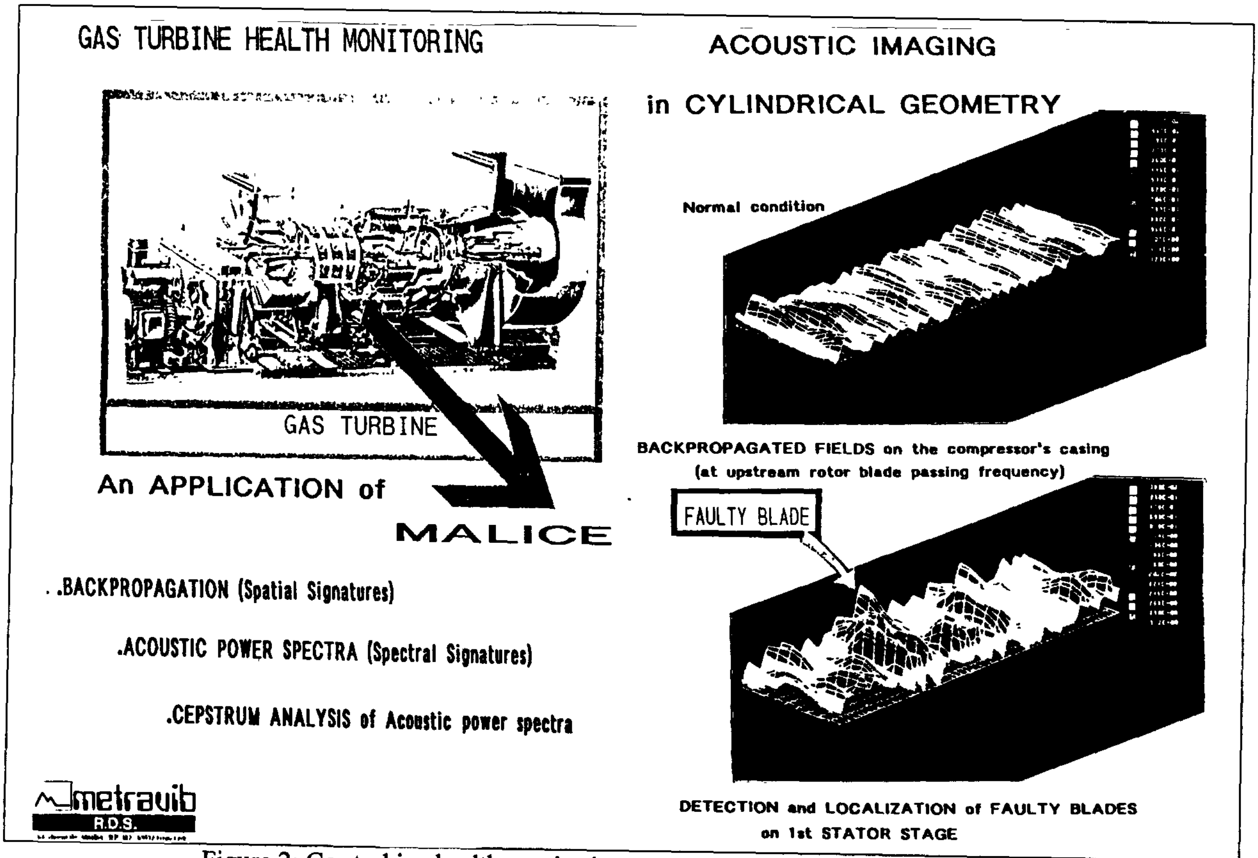

Figure 2: Gas turbine health monitoring system – Example of fault localization

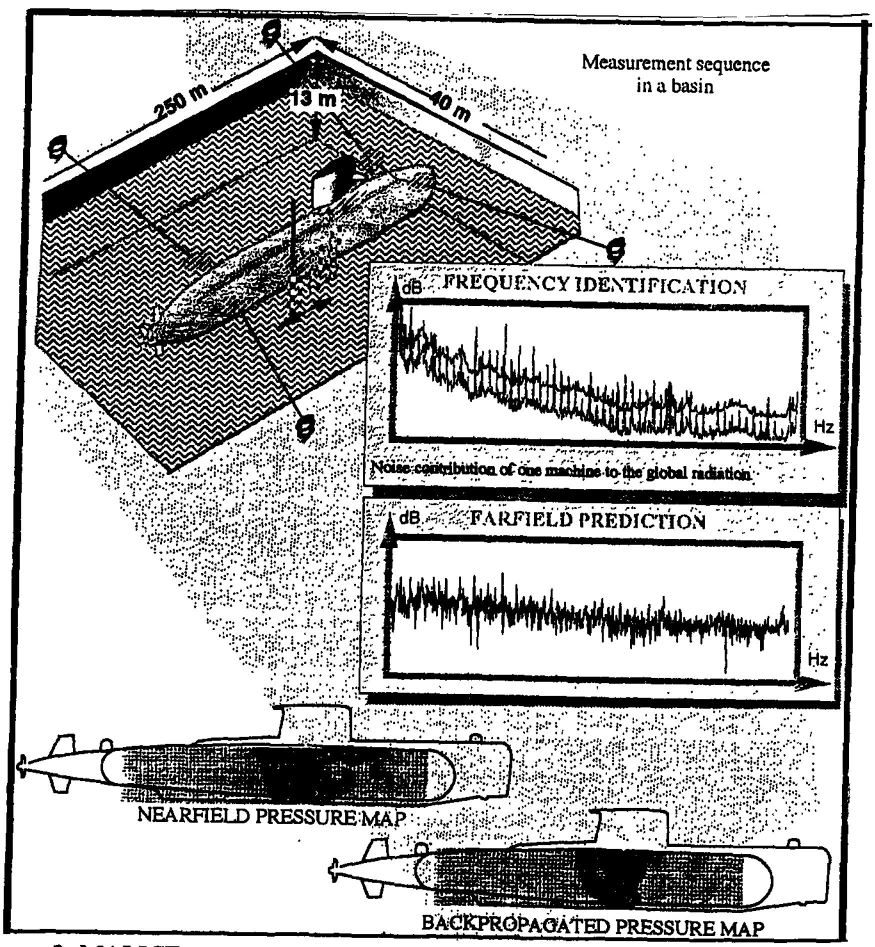

Figure 3: MALICE as a tool for noise source localization on submarines and vessels

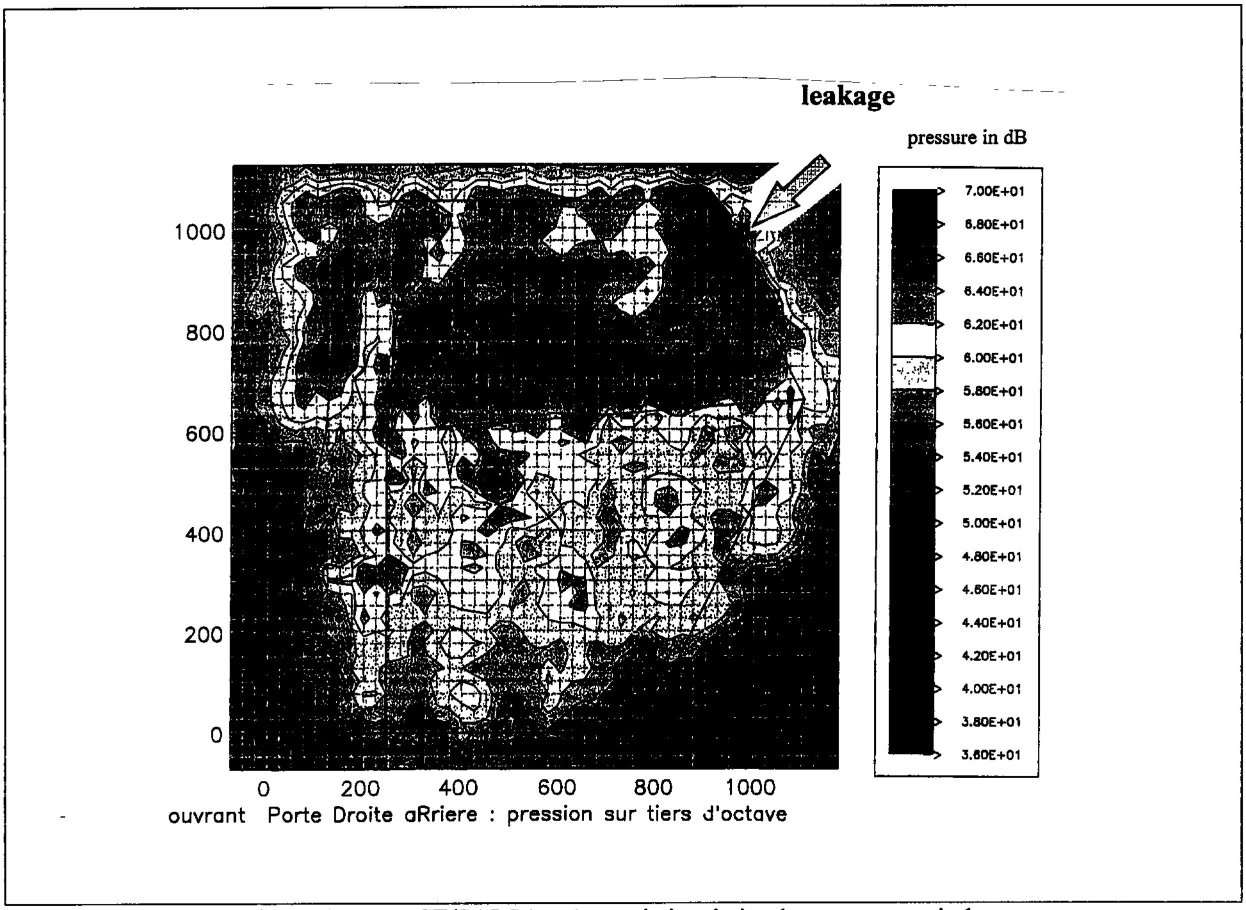

Figure 4: MALICE/SALSA – Acoustic insulation loss on a car window

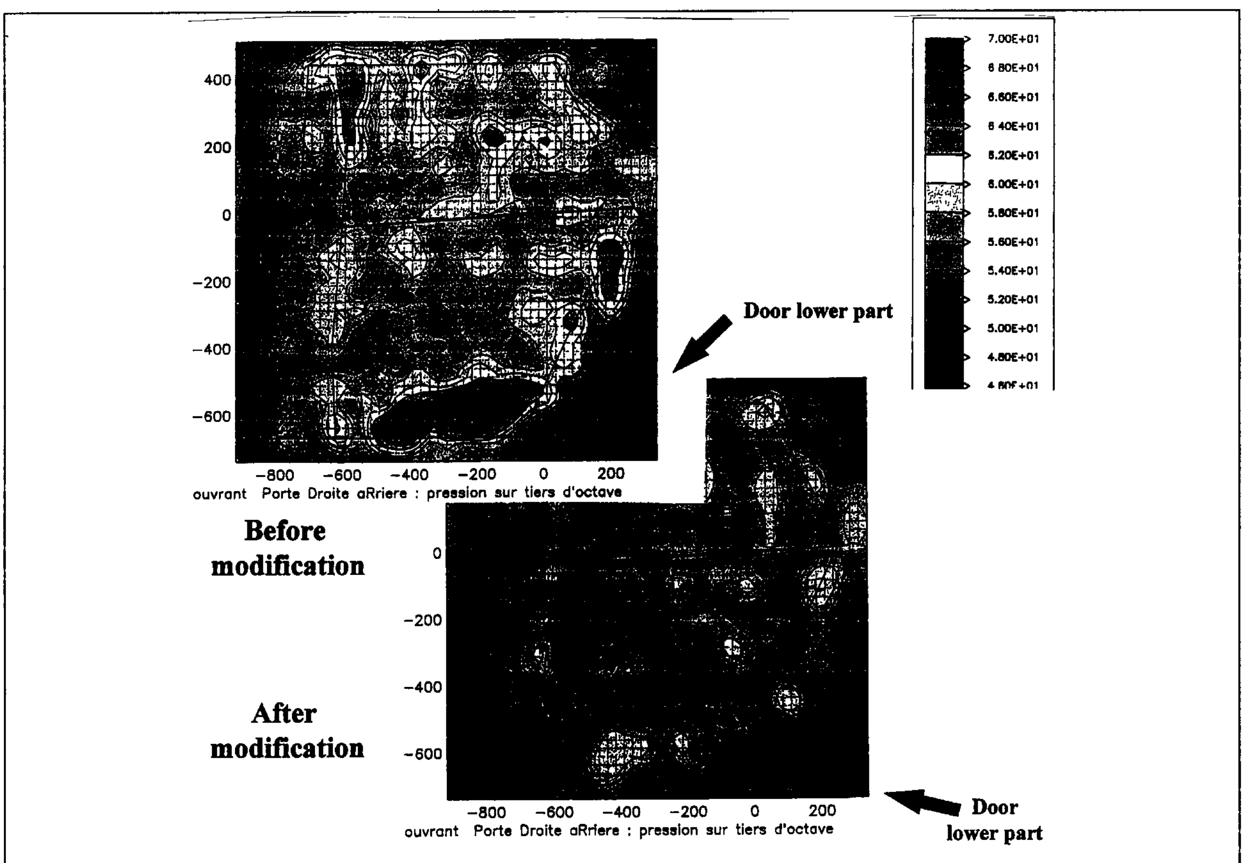

Figure 5: MALICE/SALSA – Fault correction on the rear door of a passenger car