Acoustic imaging tecniques for the identification of acoustic leaks in urban apartment blocks

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Abstract. *Sound insulation in condominium or other kind of collective urban buildings is the most important dispute subject among citizens. Dog barking, thermal or climatic systems, air extractors, music, talking, walking, etc. are just a moiety of the usual arguments of litigation. A plethora of European and Italian rules and laws classify acoustic insulation grade and minimum requirements for residential buildings, but there is a general missing attention to plenty of other maybe small details, here called "leakages", which determine the final sound isolation result.*

Even high grade sound insulation walls with R'w better than 55 dB could drive to a poor final result due to non correct assembly and mounting of stops and joints in doors and windows.

The present work presents a very practical application of the Beam-Forming Technique (BFT) to rapidly spot out several acoustic leaks types in apartment's walls.

1 Acoustic imaging tecniques

The technology of acoustical imaging has advanced very rapidly over the last decades; now it represents a sophisticated technique applied to a wide range of fields including non-destructive testing, medical imaging, underwater imaging, SONAR and geophysical exploration [1]. This technology enables sound and vibration 3D and 4D imaging in sonar, seismic, ultrasound, acoustic and medical imaging fields showing a clear common underlying theory and many similarities among these topic areas.

In the audio rendering and production fields, related technologies are the so called Wave Field Synthesis (WFS), modelling the acoustic pressure field on a plane and the so called Higher Order Ambisonics (HOA), modelling the acoustic pressure field in a spherical volume.

2 Acoustical imaging in building construction

Buildings construction techniques and materials developed from simple to complex and from wood/stone to concrete/plasterboard. The specific acoustical properties of building techniques and materials greatly influence the final sound and waves propagation among different parts of the construction. The need of a simple, reliable and cost effective sound proofing technology led to 2 mainly used technologies in the Italian market: the so called Nearfield Acoustic Holography (NAH) and the Beamforming (BF).

2.1 Nearfield Acoustic Holography

Acoustic holography is an investigation technique allowing to calculate particles sound pressure and velocity distribution in any parallel plane of the selectable measurement plane, closer or far from the source, starting from a sound pressure distribution measurement on a flat surface in front of the noise source [2].

The original acoustic holography technique was created to operate in the near field and has become a consolidated technique in industrial sectors for sound emission zones identification on complex machinery, through high resolution maps of the acoustic field, detected using a measurement plane dotted with a microphone array.

NAH operates with a matrix of microphones (regularly or sparsely distributed on a plane) in order to sample the sound field like a plane antenna, from the side of the semi-space facing the object under examination. The machinery, the plant or the sound emitting structure under examination is spotly detected and mathematically elaborated to create a superimposed image aimed to show its vibrational behaviour. The detected acoustic field is on a plane.

The total antenna width dimensions is inversely proportional to the minimum frequency to be investigated, so the lower the frequency of interest, the greater the antenna extension. NAH assumes to "see" and map the entire face of the sound source; it is also possible to sequentially move the antenna to cover the entire investigated surface.

NAH measurements are performed in the source near field, depending from the maximal frequency of interest. The microphone antenna position from the object has then to be closer than the maximal frequency wavelength (typically 20 cm); this very close positioning enables the capture of specific radiated energy information, normally invisible at higher distances.

Acoustic holography is not a real-time system, as it is necessary to mediate the acquired data over a defined time window and then computationally process them; NAH is mainly dedicated to acoustic fields with stationary characteristics.

2.2 Beamforming

Beamforming or "spatial filtering" is a signal procesing technique used in sensor arrays for directional signal transmission or reception, combining antenna array elements so that signals at particular angles constructively interfere while others destructively [3].

Beamforming (BF) was more recently developed and it is widely used. Its working principle is very similar to the aeronautical Radar, which works far from the emitting object, in order to "focus" sources of acoustic energy in a specific acoustic field at a given distance.

As in the case of a Radar, the simplest calculation algorithm for BF is the so-called "Delay and Sum", which computationally compensates the signal arrival delay of each individual microphone and adds the resulting energies; it considers the emitted sound wave at time *T* travelling the distance *D* with a delay equal to *D/c*, being c the propagation speed of a sound wave in the considered medium. The working principle assumes a propagation in an isotropic and free field, which implies that the wave sound pressure linearly decreases with distance.

Each microphone's detected signal is delayed by a time τ_i then multiplied by a weighting constant ω_i; the sum of all the microphone's weightings is equal to 1. The delays are calculated based on microphones inter-distances with respect to the direction towards which the antenna is pointed (the relative angle to the perpendicular of the antenna plane). Depending on the energy origin direction, all microphone signals will be delayed according to the specific direction "delay block" values; this last can be aligned or not and the adder result will be higher if everyone sees the same arrival angle (meaning that there is a source under that angle) or will be weak or non-existent, (meaning that there is a weak intensity source or no sound source).

The firstly developed time domain “Delay & Sum” algorithm has been upgraded in the frequency domain also, definitely improving the final results and has been gradually implemented by the various systems available on the market.

A notable advantage of BF is its capacity to work in real time and in the buildings interiors the measuring distances are normally intermediate between near field and far field. Most of the time a disturbing reverberated acoustic field is also present (typical in confined spaces); to avoid possible RT_{60} measuement disturbances, a pseudo-regular microphone distribution is applied, allowing the BF tecnique to easily overcome the problem.

3 Frequency resolution

From the point of view of an acoustic engineer, the exploitable frequency ranges of both exposed techniques do not cover the complete frequency range of interest (20 Hz - 20 kHz).
BF is very useful, direct and practical if acoustic field real-time observations are needed from enough distance and for medium-high frequencies above 200Hz, even for moving objects.
NAH is more suitable for low frequencies close to the source analyses and in stationary conditions of the acoustic field.
Based on the general acoustic holography theory, the BF arbitrary geometrical distribution of the microphones is a constraint, as the distance between the array external microphones determines the minimum wavelength that can be studied and consequently the lower investigated frequency expressed in Hz. As an example, for a 100 Hz lower frequency the antenna width should theoretically be 1.72 m broad; taking into account specific working conditions and results tolerances, it is possible to achieve good results even with a smaller array at the expense of a tolerable reduction in power focusing (acceptable results can be obtained at a 160 Hz lower frequency with an antenna diameter of just 40 cm instead of 1 m).

4 The real case

In the real case we are involved in, the main complaint is the voice perception coming from the nearby rooms between two flats. It has been known for a long time that the conversational speech fundamental frequencies for a male voice, for a female voice and for a child's voice range around 70 - 150 Hz, 150 - 250 Hz and 250 - 350 Hz respectively.
In the presented real case the used instrument is a portable BF called "Mobile Sound Viewer". It is equipped with a digital touch screen system with a microphone array providing a wide band visualization ranging from 160 Hz up to 6.000 Hz with constant high resolution (smaller acoustic spot).
The sound source is a typical dodecahedron system placed in the emitting room with sound level around 75 dB. The measuring signal is a pink noise, as it is the sound signal which is most similar to human voices.
Measurements and investigations are carried out on 3 type of partitions in a standard flat. Every measurement is recorded with photos taken during the walls scanning. The photos are automatically generated at the end of each recording, keeping in memory four shots presenting acoustic holographic images of fixed sound points of the highest found sound levels.
First partition:

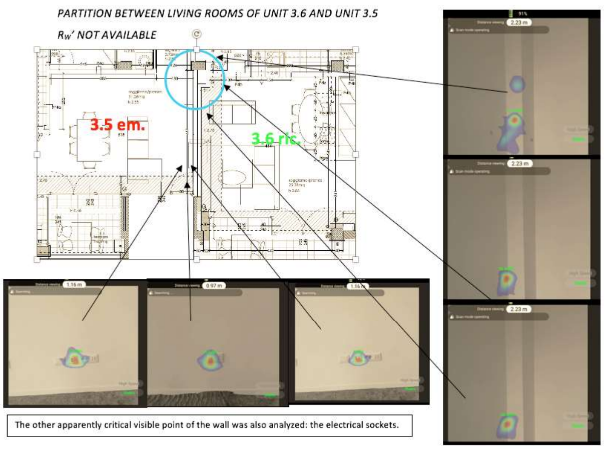

Figure 1. BF between 2 living rooms

The images of the sound transmission between 2 living rooms highlight:
the scan of the partition wall at a distance of 3-4 m seems acoustically quite uniform and nothing is predominantly highlighted;
approaching and pointing out the vertical shaft at a distance of 2.2 m (indicated with blue circles on the plans) 50-51 dB (A) are highlighted; this is a division critical element and constitutes an important acoustic bridge; further analysis reveals that this shaft was not built with juxtaposed autonomous elements to a finished layered wall; instead it was made using one of the two layers of porous brick multiple cassette wall (as indicated in the relative installation sheet);
the other apparently critical visible point of the wall is also analyzed at greater proximity, revealing that the electrical sockets sound transmission is just 44-45 dB (A);

in the upper part of the investigated wall there is a corrugated tube for a future light point, which did not show any fixed sound focus, and do not constitute a disturbing "sound passage".

Second partition

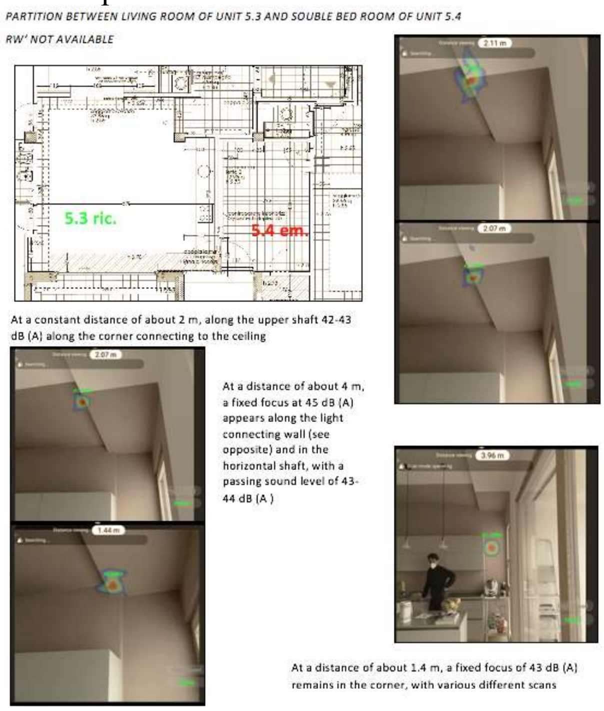

Figure 2. BF between kitchen and bedroom

Source and Receiving areas have been chosen in this way because the 2 bordering room were not completely furnished, introducing a disturbing reverberation.
In this case:
at a constant distance of about 2 m there is a fixed focus along the connecting edge of the shaft above the ceiling with a sound value of 42-43 dB (A), approximately along the first 2 m starting from the partition wall, after this distance the fixed image vanishes;
there is a constant 43 dB (A) fixed focus in the connection angle between the ceiling, the horizontal shaft and the projection towards the window, at a distance of 1.4 m;
the focus is fixed at a distance of about 4 m with a level of 45 dB (A) along the light wall connecting the porous brick wall system and the facade;
there is a fixed focus in the horizontal shaft at a distance of 2 m for about 2 m away from the vertical wall with a passing sound level of 43-44 dB (A); we suppose that the vertical shaft was not filled with at least 70 kg/m^3 heavy rock wool within the first 2 m of the light vertical wall;
we supppose an imprecise installation of the light vertical connecting partition wall (see focus at 4 m distance from the lower image).

Third partition

Figure 3. BF between 2 bedrooms

In this case the dodecahedron was placed on the double bed, in the centre of the room:
the BF wall screening did not focus any specific point except the empty space between the furniture in the bedroom with respect to the wardrobe on the side of the unit 4.5 dividing wall;
dominant sound is passing through the "lack of furniture" on the wall on the opposite side, which justifies the fact that the television is clearly heard in the living room coming from the bedroom; this implies that the sound clearly passes because of the absence of wardrobe: the entire wall is lacking in itself and even a wardrobe contributes to its

insulation; i.e. the acoustic insulation tests for the soundproofing power definition of this wall is only 42 dB of Rw;
other "acoustically weak" points are both the edge between the vertical shaft and the wall and horizontal shaft and the corresponding angle, which seems to constitute an equally "intense" acoustic bridge to the wall itself: at a distance of about 2.5 m from the closed cupboard, 43-44 dB (A) "pass" and at about the same distance from the edges/corners they pass around 42.5-43 dB (A).

5 Concluding remarks

After a theoretical presentation of the working principles of the acoustic holographic systems, we focused on the 2 specifically available on the Italian market. Italian acoustical engineers mainly use the NAH and the BF systems, as they are both reliable and cost effective, the second working in real time.
Subsequently we analyzed the working characteristics of both systems, highlighting their strengths and weaknesses.
The third part deals with a practical case, where we expose the use of Beam Forming between 2 flats in an Italian building. Here the acoustic insulation grade and minimum requirements for residential buildings are not properly respected, as there are plenty of small leakages, determining the non optimal final sound isolation result. BF allowed a relyable sound leakages measurement even in a reverberant room, making it ideal in non furnished spaces.
In deep knowledge of the BF technique allows very good spot sound visualization, depending on microphine antenna array dimensions and measurement distance, making it the reference technology for reliable, cost effective and portable building sound analysis.

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