Combined acoustic testing of home appliances: a case study

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ABSTRACT

To improve the comfort of the domestic environment, the acoustic performances of home appliances need to be optimised. During the product development stages, manufacturers typically carry out acoustic measurements to validate design strategies and to perform troubleshooting. Moreover, several experimental techniques can be used depending on the target of the analyses. In this paper, the sound field radiated by an operating washing machine is investigated. A combined acoustic testing is carried out by means of a sound intensity probe and a microphone array. The details on the tests execution and the data processing are presented. The experimental results are discussed, providing a synthesis of the two sets of measurements.

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1. INTRODUCTION

Acoustic performances are a key aspect for home appliances market. Therefore, manufacturers are committed to reducing noise generated by their products and acoustic-oriented design strategies are typically adopted during the development of new devices.

In this context, vibroacoustic experimental tests are fundamental to perform troubleshooting and supporting the development of washing machines, as testified by the research activities carried out in this field [1,2]. Focusing on acoustic measurements, sound intensity and sound mapping techniques are particularly suitable to investigate the influence of components on the radiated noise, as highlighted in previous studies [3,4].

In this work, a combined acoustic testing campaign was carried out by means of a sound intensity probe and a microphone array. The activity aims at the comparison between the two experimental approaches in terms of tests' execution and correlation of the results.

2. EXPERIMENTAL TECHNIQUES

In this section, a brief overview of sound intensity probes and the processing of microphone arrays' signals is provided. In particular, for this study, tests were carried out using a 3D sound intensity probe and a microphone array, whose acquisition were processed through Planar Near Field Acoustic Holography (PNAH) and beamforming algorithms.

2.1. Sound intensity probes

The most common device to measure sound intensity is the so-called p-p probe. This tool consists of two closely spaced microphones: their signals are processed based on a finite difference approximation to estimate the sound pressure gradient and to evaluate the component of the sound intensity vector that is parallel to the line connecting the two sensors [5-6].

However, the sound intensity is a vectorial quantity, thus three components must be measured to fully describe the amplitude and direction of the sound intensity vector. To this aim, 3D sound intensity probes can be adopted. These devices are based on an arrangement of four or more microphones that can be also embedded on a rigid spherical surface. The analytical solution to the acoustic scattering due to a rigid spherical geometry represents the main advantage of the latter configuration; moreover, its effect on the measured signals can be removed in a post-processing stage. Details on the estimation of the sound intensity vector using 3D probes are provided in [7].

2.2 Planar Near Field Acoustic Holography (PNAH)

The Planar Near Field Acoustic Holography is a technique based on near field measurements through a planar array of microphones. Acoustic pressures are evaluated on the array surface and measurements are processed in order to describe the sound field based on propagating and evanescent planar waves, represented by the set of wavenumbers (k_x, k_y, k_z). From this description, the sound field can be projected onto any other plane parallel to the measurement one through a processing based on Green's function. Eventually, the sound field is reconstructed on the plane containing the noise source and the results are visualized as 2D colormaps, so that regions with higher sound emissions can be located. Further details on this technique are provided in [8].

The PNAH technique is particularly suited for the investigation of the low frequency range since the inclusion of evanescent waves guarantees superior resolutions with respect to other approaches. Conversely, in order to investigate the high frequency range, the beamforming technique provides better results with respect to PNAH, provided that the same number of microphones is considered.

2.3. Beamforming

According to the beamforming technique, sound sources are modelled as monopoles and a spherical sound wave propagation model is considered. In this condition, an observer at a distance r from the source perceives a signal with a delay equal to r/c, being c the speed of sound. Thus, considering an array of microphones and an arbitrary sound source, each sensor measurement is affected by a certain time delay. Provided that these are compensated for, then signals reinforce each other and their summation is maximized, that is the principle behind the Delay and Sum (DAS) beamforming techniques: in the end, the source location is identified on the plane of the emitter maximizing the delayed sum of the microphones' signals [9,10].

In case of planar arrays, the spatial resolution of the beamforming technique increases linearly with the frequency, thus providing better results in high frequency ranges. Benefits can be obtained also increasing the dimensions of the array.

3. MEASUREMENTS

In this paper, the experimental techniques described in Section 2 are considered for the evaluation of the sound intensity field of an operating washing machine. In particular, the test case focussed on the right side of the device, thus the lateral panel was scanned covering a surface of approximately 50 cm x 80 cm. Tests were performed in controlled conditions, driving the washing machine at a constant speed and reproducing a typical load condition. The acoustic measurements were performed in a semi-anechoic chamber whose cut-off frequency is lower than 150 Hz.

(a)

(b)

Figure 1: the 3D sound intensity probe (a) and the microphone array (b) used during the experimental campaign.

During the tests, a 3D sound intensity probe and a microphone array were employed. On the one hand, concerning the sound intensity probe, a G.R.A.S. 3D Vector Probe Head Type 60LK was used (Figure 1a). This device is made of four ¼" microphones embedded in a rigid spherical surface. The acquisition chain was completed with a signal conditioner and a data acquisition module. On the other hand, the microphone array adopted during this activity was a Brüel & Kjær Acoustic Camera

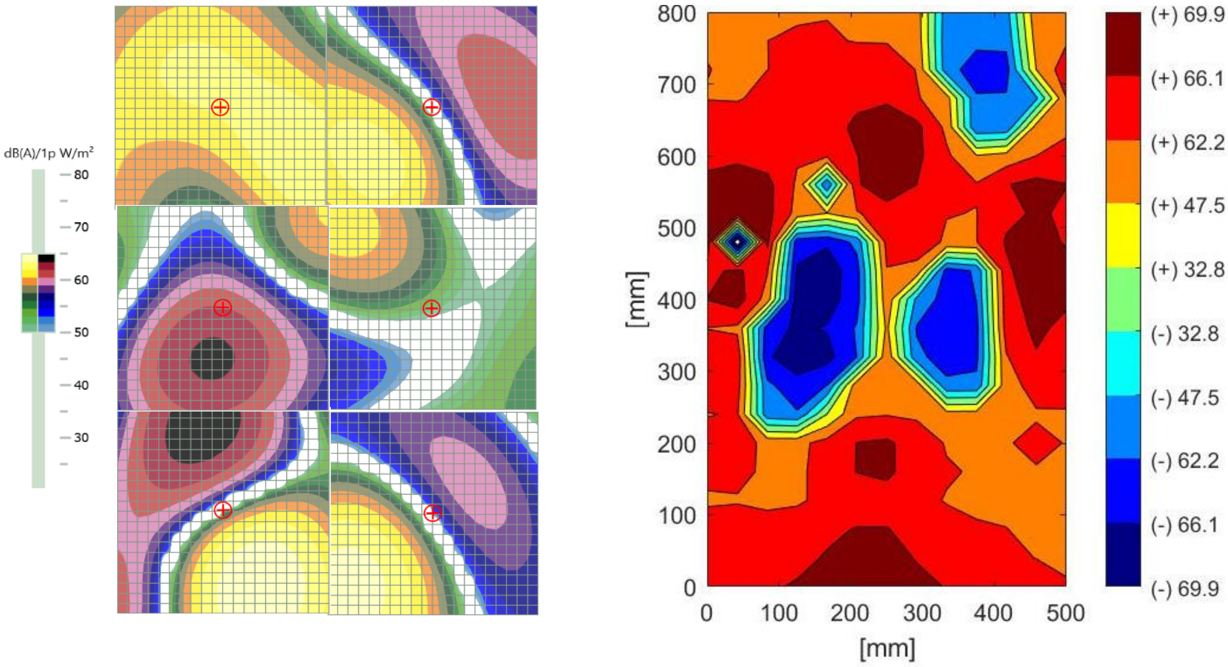
Type 9712-W-FEN (Figure 1b), made of a disk of approximately 30 cm diameter with thirty ¼" prepolarized microphones. Together with its dedicated acquisition system, this device is suited for both acoustic holography and beamforming measurements.

At first, tests with the sound intensity probe were carried out. The lateral panel of the washing machine was scanned by placing the probe at a distance of 5 cm from the panel and using a rectangular grid with a 4 cm spatial resolution, for a total of 273 measured positions. For each position, a 2 s acquisition was performed and then the sensor was manually moved to the following measuring position until the whole scan was completed. Secondly, tests were performed with the microphone array. In this case, nearfield measurements were performed in order to evaluate the sound intensity on the same plane of the sound intensity probe. To this aim, taking into account the array dimensions with respect to the panel, the scan was performed by dividing the panel into six areas and performing consecutive acquisitions. No repeatability issues are expected due to the controlled environmental and operative conditions in which tests were carried out. Eventually, the microphone array was also used to perform far field measurements at a distance of 1 m from the panel, so that the beamforming technique can be also applied to process the signals and carry out analysis in the high frequency range.

4. RESULTS AND DISCUSSION

Once the experimental campaign had been completed, the results were evaluated in terms of 2D colormaps of the sound intensity vector component normal to the panel. Moreover, measurements were processed in order to represent the results in terms of A-weighted sound intensity levels in one-third octave bands. The data processing of the microphone array was performed through the dedicated BK Connect Type 8430 Array Analysis software for both acoustic holography and beamforming cases. Instead, a dedicated MATLAB code was developed to process and visualize the data acquired by the 3D sound intensity probe. In this case, a correction of the acoustic scattering due to the sensor's rigid spherical surface was performed, then the sound intensity vector was evaluated for each of the 273 measurement positions and eventually the colormaps of the normal component of the sound intensity vector were represented.

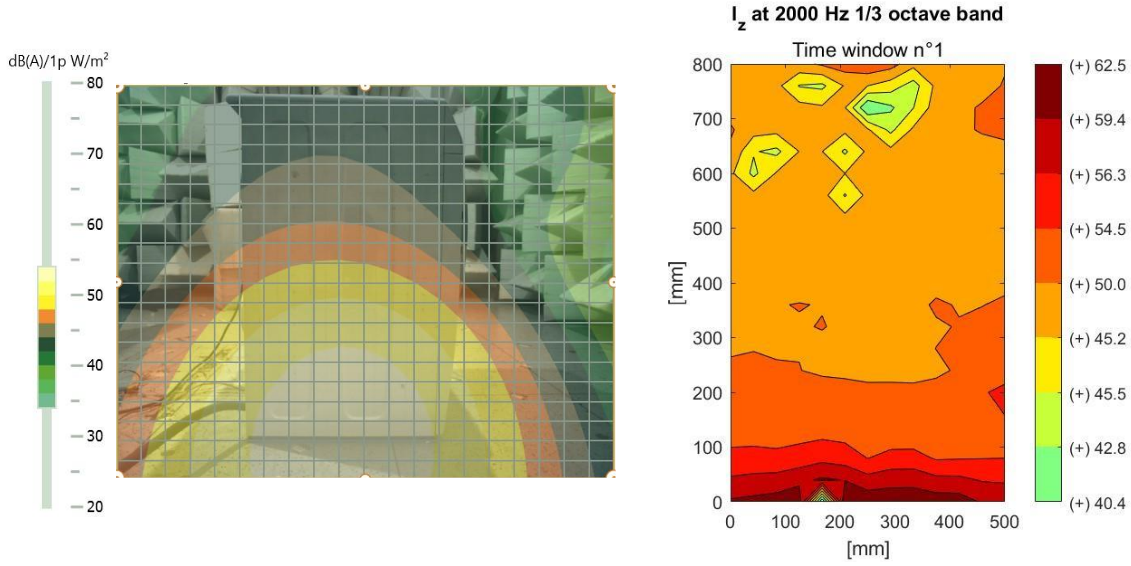
At first, results were evaluated in order to perform a comparison between tests with the sound intensity probe and the acoustic holography ones. To this aim, taking into account that the latter technique is particularly suited for the investigation of the low frequency range, the 200 Hz one-third octave band was investigated. The resulting colormaps are represented in Figure 2. In particular, in Figure 2a, the outcomes of the acoustic holography are reported combining the six portions of the scan. The results show an acceptable match between the six areas, thus validating the tests execution. In this colormap, the sound intensity is represented using two different colorbars. The first one is related to positive values of sound intensity normal component (the sound intensity vector is directed outwards with respect to the washing machine panel), whereas the second one represents negative values (inwards sound intensity vector). The presence of regions with negative values of normal sound intensity is a phenomenon that was observed up to 630 Hz for the panel under analysis. However, it was verified that, integrating the normal sound intensity over the surface of the panel, a positive sound power flowing from the panel to the surrounding environment was obtained. Similar considerations can be made for the colormap obtained from the 3D probe test (see Figure 2b). In this case, a unique colorbar is adopted: colours ranging from yellow to dark red stand for a positive normal sound intensity, whereas colours ranging from light blue to dark blue are related to negative values. Observing the colormap, a smooth transition between the different area of the scan is obtained, even though few localized abrupt transitions from positive to negative normal intensities can be observed. In this case, probably some undesired sources of disturbance affected the acquisitions, especially considering that the sensor was manually moved by the operator along the grid, and he might accidentally generated noise during the tests. Nonetheless, the quality of the results can be regarded as satisfactory. Comparing the results of the two techniques (shown in Figure 2), a good match between the two colormaps is obtained. In particular, the transition between areas with positive and negative normal sound intensities is coherent between the two datasets. The results are in accordance also in terms of absolute values if a margin of 3-4 dBA is accepted.



(a) (b)

Figure 2: A-weighted sound intensity levels in the 200 Hz 1/3 octave band. In (a), the results of the acoustic holography, in (b) the outcomes of the sound intensity probe test.

Secondly, a comparison between the results of the 3D sound intensity probe and the microphones array was performed focussing on a medium-high frequency range. In this case, the results are presented considering the 2 kHz one-third octave band and the processing of the acoustic camera measurements was based on a beamforming algorithm. Due to the higher distance between the sensors and the washing machine, in this case a unique acquisition was required to scan the whole surface of the panel, as represented in Figure 3a. To complete the comparison, the results of the 3D probe are represented in Figure 3b. The results considering other bands are omitted since similar conclusions can be made comparing the two techniques (from 1 kHz on). In particular, both techniques prove the bottom end of the washing machine to be related to higher levels of sound intensity. Moreover, compared with the results achieved at the low frequency range, it can be observed that a positive normal intensity is always obtained all over the panel's surface. Focussing on the results of the sound intensity probe (Figure 3b), also the upper right part of the panel shows high intensity levels, probably related to the presence of the detergent drawer. By contrast, the upper left side of the panel is characterized by lower levels of sound intensity. These results are valid also for other bands starting from 630 Hz.



(a) (b)

Figure 3: A-weighted sound intensity levels in the 2000 Hz 1/3 octave band. In (a), the results evaluated through a beamforming approach are shown, whereas in (b) the outcomes of the sound intensity probe tests are reported.

5. CONCLUSIONS

A combined acoustic testing was carried out by means of a sound intensity probe and a microphone array. The aim of this activity was a comparison between the two experimental approaches for mapping the sound intensity levels of the lateral panel of an operating washing machine. Tests were carried out in controlled operative conditions, acquiring the signals with both the 3D sound intensity probe and the microphone array. The results show that the measurements of the microphone array well correlate with those of the sound intensity probe. In conclusion, both approaches can be useful for the investigation of the sound field of a generic home appliance and to perform troubleshooting during the development of new products.

6. ACKNOWLEDGEMENTS

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