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EXPERIMENTAL APPROACHES FOR THE CHARACTERIZATION OF THE VIBROACOUSTIC BEHAVIOUR OF A DOMESTIC COFFEE APPARATUS

Federico Castellini*[1] **Arianna Cavallo[1]** **Marco Rossoni[1]** **Francesco Ripamonti[1]** **Giorgio Colombo[1]** **Roberto Corradi[1]** **Gennaro Cimmino[2]**

[1] Department of Mechanical Engineering, Politecnico di Milano, Via Giuseppe La Masa 1, 20156 Milan

[2] De'Longhi Appliances S.r.l., Via L. Seitz 47, 31100 Treviso, Italia

ABSTRACT

The growing demand for more comfortable and quieter household appliances reflects the increasing customer expectations for enhanced user experiences. In a competitive market, manufacturers are continuously seeking innovations that balance performance with noise reduction. To address this demand, experimental methodologies that characterize the vibroacoustic behaviour of devices can provide valuable support during the design phase. In this context, this paper focuses on a domestic coffee apparatus for coffee preparation as a case study to analyse its vibroacoustic behaviour, evaluating the acoustic emissions during operation and demonstrating the effectiveness of vibroacoustic testing for enhanced design insights. Noise and vibration measurements are conducted in a semi-anechoic chamber using accelerometers, microphones, a sound camera and a 3D sound intensity probe. The results of the proposed methodology highlight its potential for improving the acoustic performance of similar devices.

Keywords: *sound power, beamforming, sound intensity measurements, noise localization, vibroacoustic analysis*

**Corresponding author*: federico.castellini@polimi.it

1. INTRODUCTION

In recent years, domestic comfort has become a relevant aspect for customers, who require household appliances that are not only efficient but also quiet. In a competitive market, the attention to technical solutions that reduce acoustic impact without compromising performance is in constant growth. To this end, the adoption of experimental and numerical methods to study the vibroacoustic behaviour of such devices is one of the key elements in the process of product development and optimization.

The article presents a methodology to characterize in detail the vibroacoustic performance of a generic household appliance. The methodology is applied to a domestic apparatus for coffee preparation as a case study. The outcomes of a set of experimental approaches are compared, highlighting the potential benefits and the main limitations of adopting different measurement techniques and data processing methods. The procedure is designed to establish a setup that identifies the primary noise and vibration transmission paths, providing guidelines for acoustically driven design improvements or optimizing the acoustic performance of the product under analysis. The overview of the methodology is provided in Section 2. The preliminary acoustic analysis of the coffee machine is carried out in Section 3 through sound pressure and sound power measurements [1]. The detailed acoustic characterization of the product is described in Section 4. The identification of the main noise sources is conducted through beamforming algorithm [2] and sound intensity measurements [3]. The spatial reconstruction of the noise generated by the machine is suitable for the definition of a hybrid setup including accelerometers and microphones for the identification of the main acoustic and vibration transmission paths, which in turn allows for the definition of possible mitigation actions and the evaluation of their effectiveness.

2. METHODOLOGY AND TEST CASE OVERVIEW

The most commonly performed acoustic tests for characterizing a product's acoustics rely on sound pressure measurements and sound power calculations (Figure 1a). These approaches only provide the possibility to have a general description of the product and do not allow for the identification of the location of the critical noise sources. In parallel with these measurements, noise source localization analysis is performed using a beamforming algorithm applied to a microphone array or by employing sound intensity measurements (Figure 1b). The combination of these two sets of tests enables a detailed characterization of the machine's acoustic behaviour, offering guidelines for developing a refined vibro-acoustic setup aimed at achieving a comprehensive vibroacoustic analysis (Figure 1c).

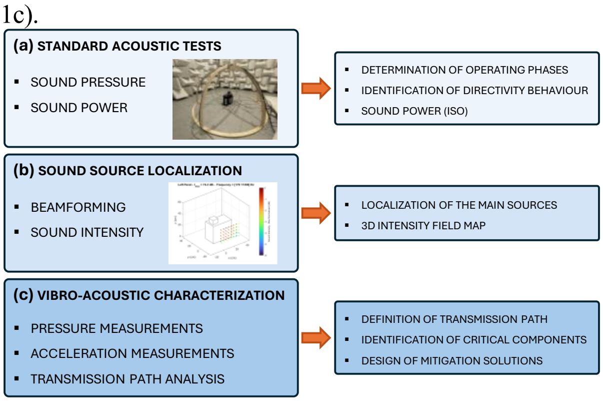

Figure 1. Overview of the methodology: (a) standard pressure and power measurements, (b) sound source localization techniques and (c) comprehensive vibro-acoustic characterization.

The machine under examination features an internal supporting frame that houses the components (motors, coffee grinder, handling and brewing systems) along with the external panels. Excluding components that are not involved in the grinding phase (the only operational phase analysed in this paper), the machine can be schematized as a combination of the following components. The "source group", consisting of the motor and grinding system, is positioned inside the machine and supported by the frame via supports. It is also connected to the coffee bean container through a channel passing through the upper panel. The external panels are, in turn, connected to the frame. Ventilation grids are installed on each panel, necessary for cooling the electrical circuits and for dissipating condensation (see Figure 2).

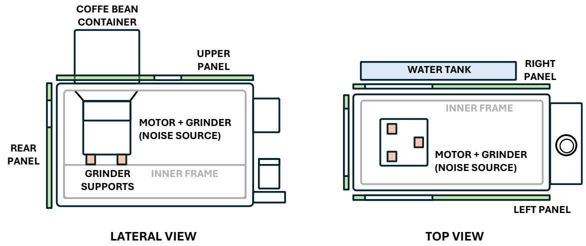

Figure 2. Schematic overview of the coffee machine. The ventilation grids on the external panels are indicated with a, b, c and d.

3. IDENTIFICATION OF THE ACOUSTIC BEHAVIOUR

The acoustic behaviour of the coffee machine is determined through a preliminary assessment of pressure measurements and sound power calculation. The analysis is carried out using a hemisphere (1m radius) designed for sound power measurements (ISO 3744 [1]). Measurements are conducted with 10 microphones located in different positions of the sphere, measuring the sound pressure in the position highlighted in Figure 3.

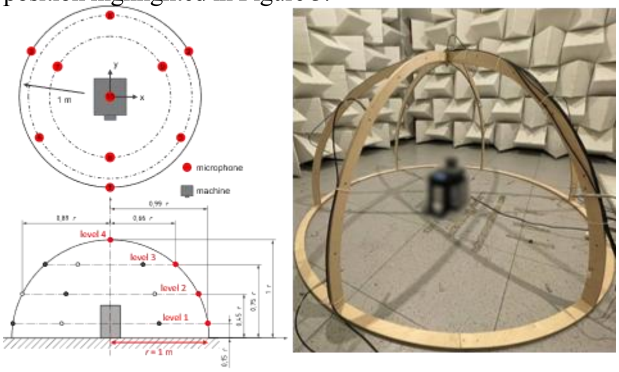

Figure 3. Setup of the sound power measurements [1].

Data from these microphones can be first used to highlight the different operating phases of the machine and to highlight possible non-stationary behaviour during each phase. This is performed by computing sound pressure levels using the fast-weighting data processing (see [4]), which allows for estimating the total sound level over time. The results of this procedure are collected in Figure 4a.

Microphone 10 is considered (see the scheme of Figure 3). The operating phases of the coffee machine (grinding, brewing and internal movement operations) are clearly evident when observing the overall Sound Pressure Level (SPL) over time ($p_{ref} = 2{\cdot}10^{-5}$ Pa). The grinding phase is the most critical and the loudest operational phase, as shown in Figure 4a. A time-frequency domain analysis is also conducted to highlight any critical frequencies associated with the noise phenomena. The spectrogram of the noise levels recorded by microphone 10 is shown in Figure 4b.

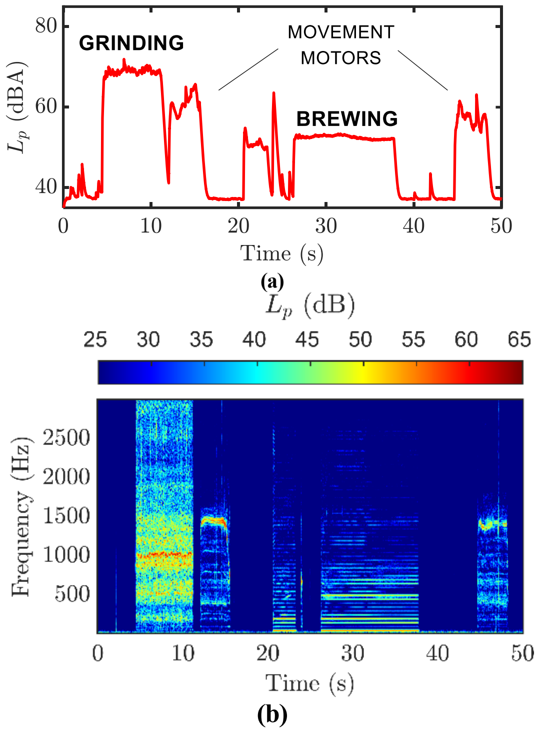

Figure 4. Identification of the machine operational phases (microphone 10): (a) fast weighted SPL (dBA) and (b) spectrogram (dB).

The noise generated during the grinding phase is mostly concentrated in the one-third octave band at 1 kHz and is related to the interaction between the grinder and the coffee beans. During the motor movement phase, it is possible to highlight that most of the noise is concentrated around 1500 Hz, which corresponds to the frequencies associated with the rotation of the motor that moves the coffee container to prepare the brewing phase. A peculiar frequency pattern is highlighted during the brewing phase, where it is possible to recognize the contribution of the motor pump, which is directly powered by household electricity (generating noise at the main electric frequency and at the higher order harmonics). In this research, the focus is given to the analysis of the grinding phase, which is, as explained above, the most annoying one considering the noise levels and the high-frequency content. All the following analyses are related to this phase only. One of the most important outcomes of the sound pressure measurements using a hemisphere in a hemi-anechoic chamber is the sound power of the machine, which can be computed following the procedure reported in ISO3744 [1]. Sound power provides an overall description of the noise generated by the machine and allows for comparison between similar products, as reported in Figure 5, where the sound power levels of the described reference Coffee Machine (CM1) are compared with those computed from sound pressure measurements of three other similar devices (CM2, CM3, CM4).

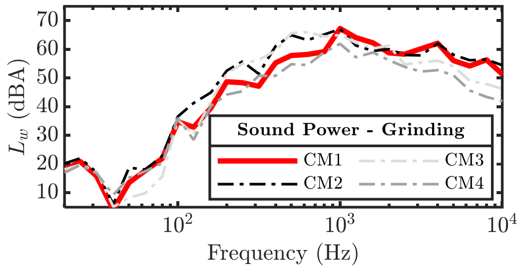

Figure 5. Third-octave band sound power levels of the grinding phase for different Coffee Machines (CM).

It must be noted that sound power can be considered a good index for initial assessment or for comparison between similar devices, but also to evaluate the overall impact of possible mitigation solutions. However, sound power is the result of the integration of the sound intensity normal to the hemisphere, so it represents the sum of the contributions of all the noise sources, which can also be localized in specific areas of the machine. Thus, to achieve a comprehensive acoustic characterization, further analysis is required, focusing on sound source localization and identification.
The techniques required to achieve these objectives are described in Section 4.

4. DETAILED ACOUSTIC CHARACTERIZATION

This section presents the techniques used for a detailed acoustic characterization by identifying the main noise sources. Preliminary sound source localization is conducted using a beamforming algorithm applied to measurements taken with a microphone array. Further investigation is carried out through sound intensity measurements.

4.1 Preliminary sound source localization through acoustic camera

The delay and sum algorithm, which serves as the foundation of beamforming [2], is one of the most common techniques adopted to locate the main sound sources on complex systems. Beamforming is typically employed to process the signals measured by one or more microphone arrays, enabling the generation of the beampattern, which is an acoustic map that highlights the loudest sound sources over a reference plane. In this research, preliminary sound source localization is carried out through the acoustic camera type 9712-W-FEN by Bruel & Kjer [5], which allows for obtaining real-time visualization of the acoustic field around the object analysed. In this context, the camera is used to scan each panel of the coffee machine by moving the microphone array. The acoustic maps of the left, right, rear, and top/upper panels are reported in Figure 6a, 6b, 6c, and 6d, respectively.

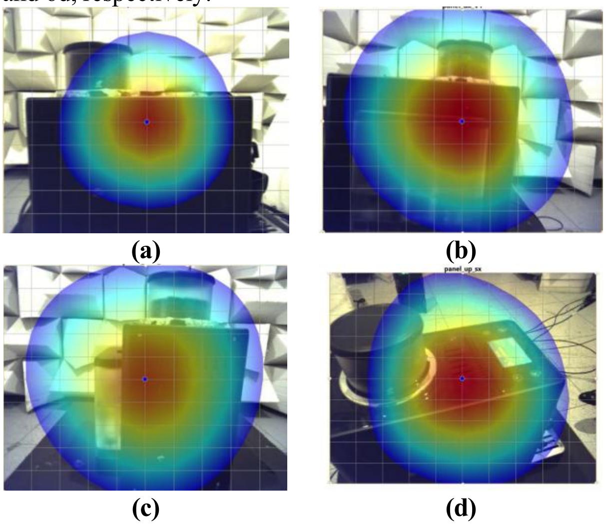

Figure 6. Results of the beamforming analysis through the acoustic camera: (a) left panel, (b) right panel, (c) rear panel and (d) upper panel.

The main noise emission is found to be located close to the ventilation grids, suggesting that this area may be the most significant transmission path for the noise produced in the internal part of the machine as a result of the vibrations generated during coffee bean grinding. However, the acoustic map produced by the camera may not always provide accurate noise level results due to several limitations. The operator's movement during the acoustic scanning process causes variations in the relative position between the microphone array and the source, introducing errors. Additionally, the beamforming technique has limited spatial resolution at low frequencies, making it less effective in accurately locating low-frequency noise sources. It is also sensitive to environmental reflections and background noise, which can distort the identification of sound sources. Moreover, when multiple noise sources are close to each other and operate at similar frequencies, beamforming may struggle to separate them clearly. In conclusion, it is able to provide only a qualitative representation of noise distribution rather than absolute sound intensity values. For this reason, in the next section, the noise generated by the machine will be accurately mapped using sound intensity measurements.

4.2 Detailed sound source identification: 3D sound intensity map

Sound intensity measurements can be used to refine the results obtained through the acoustic camera by reconstructing the sound intensity field surrounding the machine. To this end, a G.R.A.S. 3D sound intensity probe head type 60LK is used to estimate the sound intensity vector in different positions close to the left, right, rear, and top panels (see Figure 7).

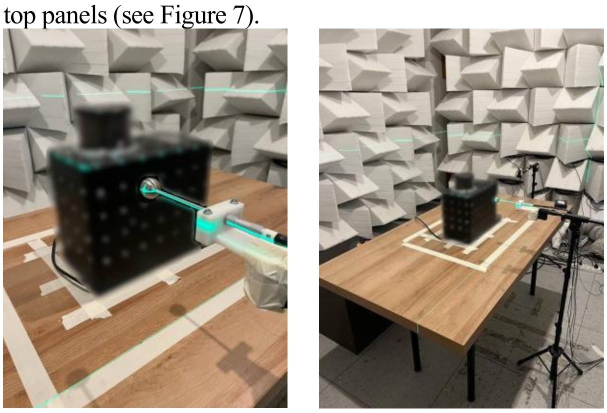

Figure 7. Measurement setup of the sound intensity measurements.

The measurements are carried out thanks to four ¼" microphones embedded in a rigid spherical shell with a diameter of 30 mm, which are organised in a regular tetrahedron configuration. A dedicated MATLAB software was developed to process and visualize the data acquired by the 3D sound intensity probe. In this process, a correction was applied to account for the acoustic scattering caused by the sensor's rigid spherical surface in the acoustic field, following the formulation proposed in [6,7]. The output of the algorithm is the estimation of the sound intensity vector at the centre of the sphere, which allows tracking the magnitude and the direction of the sound intensity field in different positions surrounding the coffee machine. During the tests, the sound probe is positioned 15 cm from each of the panels. A total number of 118 measurement points is created, adopting a spatial distance between points of 5 cm. Unlike beamforming, sound intensity measurement offers higher accuracy in quantifying noise levels, is less affected by background noise, and allows for direct identification of sound transmission paths. Additionally, it enables analysis in low-frequency ranges and provides vectorial information about the direction of the sound energy flow, offering a more detailed characterization of noise sources. Another key advantage is its ability to analyse both near-field and far-field noise propagation, making it particularly useful for distinguishing between localized sources and the overall noise radiation of the machine. The results of the sound intensity measurements are reported in Figure 8. The sound intensity vectors are normalised with respect to the maximum value obtained in each panel. The analysed frequency range includes all one-third octave bands from 200 Hz to 10 kHz. A colormap of 6 dB is employed for the sound intensity field representation. The maximum value of sound intensity (78.1 dB) is obtained on the upper panel, just in front of the top grid. Slightly lower sound intensity magnitude is obtained on the rear panel (77.7 dB) and on the left and right panels (74.2 dB and 73.5 dB). The differences between the left and the right panels are due to the presence of the water tank on the right side, which creates an additional shield for sound transmission.

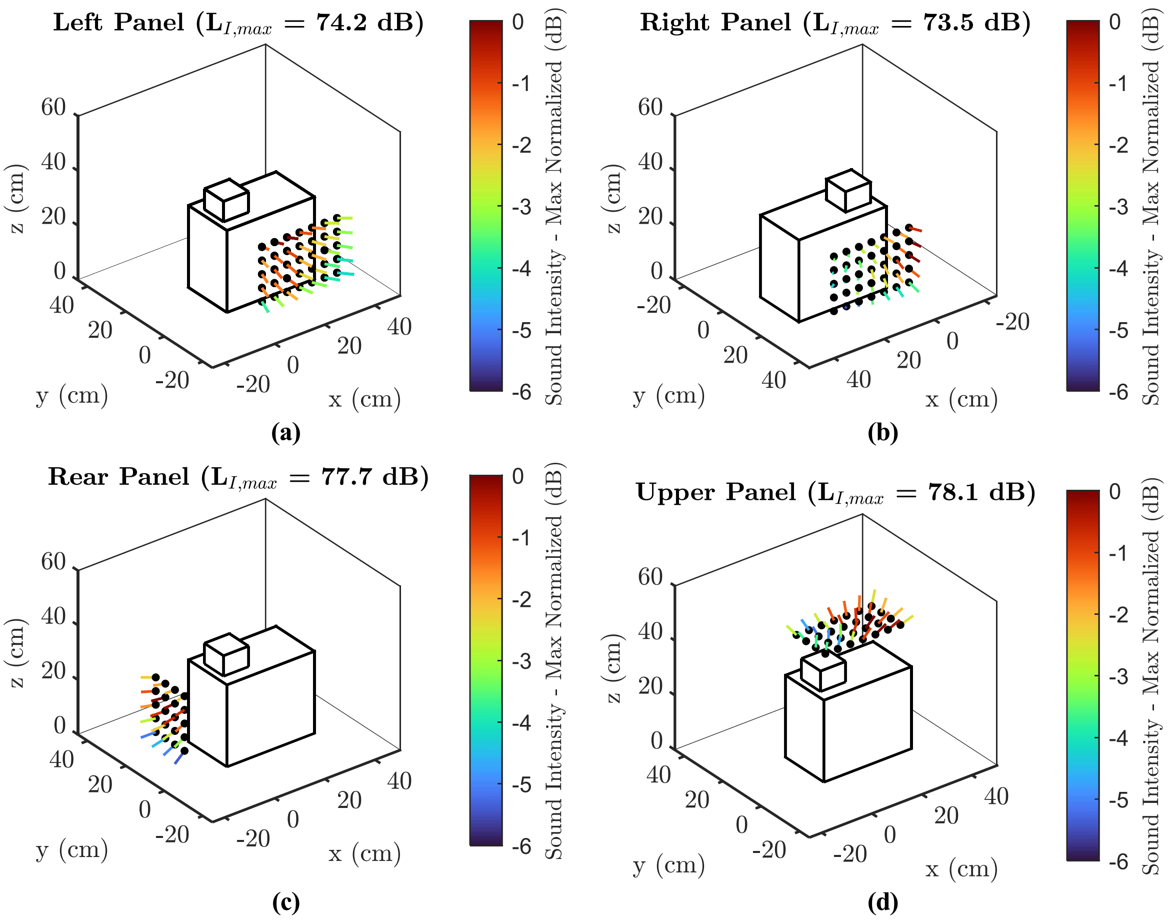

Figure 8. 3D sound intensity maps: (a) left panel, (b) right panel, (c) rear panel and (d) upper panel.

5. VIBROACOUSTIC ANALYSIS

The identification of the sound sources through beamforming and sound intensity measurements reveals some localized potential critical areas associated with noise emission during the grinding phase. Thus, a measurement setup dedicated to further refinement of these findings has been developed. The main scope of this third experimental session is to understand if the noise is mostly generated by acoustic leakages, such as the ventilation grids, or if there are other phenomena associated with structural contributions only. Determining noise and vibration transmission paths is fundamental to identifying potential mitigation solutions. This analysis requires not only pressure measurements but a combination of noise and vibration tests. A hybrid setup is therefore designed, including accelerometers and microphones mounted in different positions. The description of the measurement setup is provided in Section 5.1, while the results of the tests are analysed in Section 5.2.

5.1 Measurement setup

The final tests are carried out by organising sensors in three layers: source sensors (layer 1, accelerometers), "near field" sensors (layer 2, accelerometers and microphones at 5 cm relative to the ventilation grids) and "far field" sensors (layer 3, two microphones located 1m away from the front and the rear of the coffee machine). Please note that layer 3 has been designed to be representative of a generic customer position. These sensors are useful for estimating the average noise level to which the user is exposed during the coffee preparation and to investigate the possible impact of different design solutions on user annoyance. This is not the aim of the present paper, so the analysis of layer 3 is not reported here. The overview of the entire setup is illustrated in Figure 9.

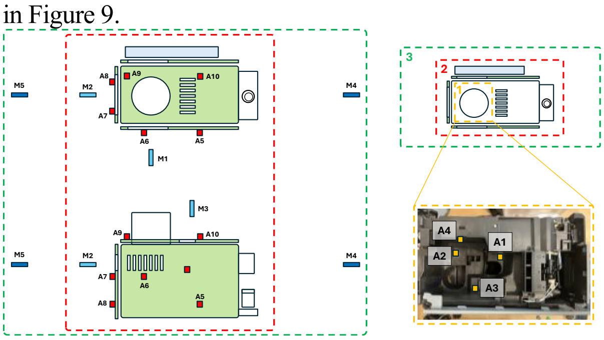

Figure 9. Refined setup for vibro-acoustic characterisation.

5.2 Transmission path analysis

Three of the four accelerometers of layer 1 are mounted close to the supports of the grinder, and they collect the vibration transmitted by the source to the main frame of the machine. As highlighted in Figure 10, these supports are not the only possible structural transmission path for vibration induced by the grinding process. In fact, the grinder is connected to the upper panel also through the canal for the passage of coffee beans from the coffee container. The main challenge is to determine the impact of the possible transmission path. This is carried out by comparing the vibration measured by the accelerometers mounted on layer 1 and the sensors mounted on layer 2.

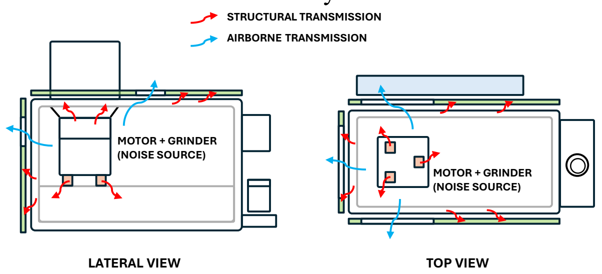

Figure 10. Identification of potential structural and acoustic transmission paths.

First, the comparison between the acceleration measured on the inner frame (layer 1) and that of the panels is performed. The spectrogram of the acceleration levels ($a_{ref}=1\cdot10^{-6}$ m/s) is employed. The most important results of the analysis are now presented. The accelerometer 1 (A1) is chosen as the reference channel for layer 1, while A5, A8, and A9 are the reference channels for the left, rear, and top panels, respectively. The results are reported in Figure 11. Similar vibration contributions are observed comparing the acceleration measured by A1 and the ones measured by A5 and A8 (left and rear panels). A low-frequency dynamic amplification is detected on the panel's accelerometers only (below 500 Hz) and it is therefore attributed to the panel dynamics. However, as it will be visible in the microphone data, the low-frequency vibration does not contribute significantly to the noise emission. The vibration peaks observed in A1 around 1 kHz are also partially visible on the left and rear panels, although they are significantly attenuated compared to the layer 1 measurements. A different vibration pattern is observed in the spectrograms of the levels of channel A9. The contribution at 1 kHz is much more evident here and is correlated with the measurements from the layer 1 accelerometers. Strong transient peaks in the vibration levels are observed at t=5s, t=6s and t=7.5s. These vibration peaks are related to the random hits generated during the grinding of coffee beans and seem to be much more evident in the top panel vibration compared to the other panels or to the layer 1 accelerometers (see A1 spectrogram). This confirms that there is a direct structural transmission of vibration from the grinder to the upper panel, in addition to the transmission of the vibration from the grinder support to the inner frame (as highlighted by looking at the correlation in the spectrograms of A1, A5, and A8).

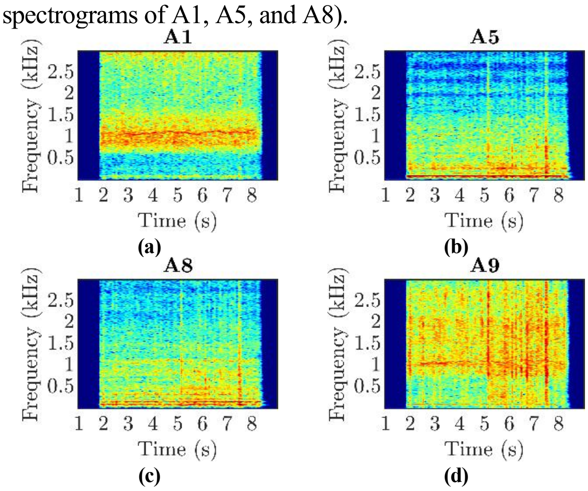

Figure 11. Spectrograms of the vibration levels (dB): (a) A1, (b) A5, (c) A8 and (d) A9.

The impact of the structural transmission on vibration can be evaluated by analysing the signal measured by the microphones located surrounding the coffee machine. The analysis of the grinding phase is repeated by closing the ventilation grids to discover if the noise emitted is mainly due to the structural transmission of the vibration from the grinder to the panel (which results in noise radiation) or if it is due to the acoustic transmission through ventilation grids. The results on the rear and the upper panels are shown in Figure 12 and Figure 13, respectively. As mentioned above, the low-frequency vibration of the panels is not found to generate a significant contribution to the noise emission (see Figure 12b). The rear panel vibration spectrogram (A8) is very similar to the one of the rear microphone (M2) at frequencies above 300-400 Hz. However, in the test with the ventilation grid closed, a significant reduction in the noise levels measured by M2 is observed (see Figure 12d). This confirms that a significant part of the noise radiated by the machine seems to be transmitted through the ventilation grids. Similar results are obtained by analysing the left panel.

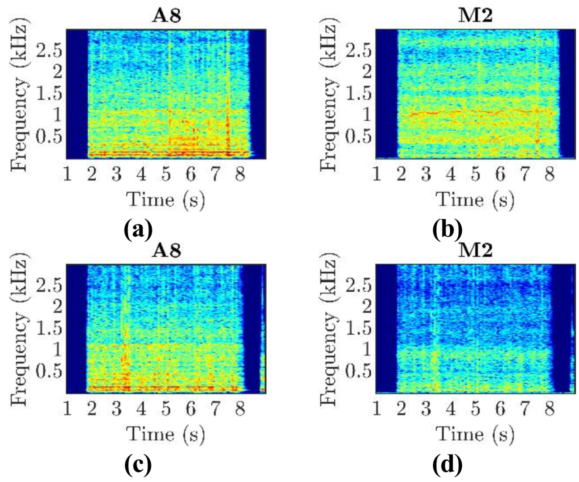

Figure 12. Spectrograms of noise and vibration levels (dB) on the rear panel: (a,b) with ventilation grids open, (c,d) with ventilation grids closed.

The analysis of the upper panel comparing the tests with the ventilation grids open and closed (see Figure 13) confirms the previous considerations regarding a possible structural transmission of vibration between the grinder and the upper panel.

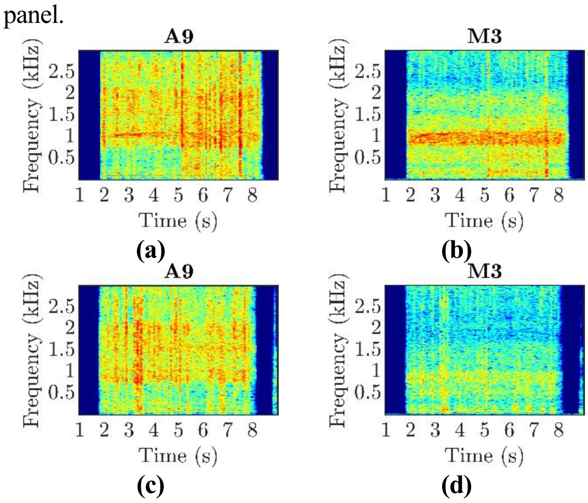

Figure 13. Spectrograms of noise and vibration levels (dB) on the upper panel: (a,b) with ventilation grids open, (c,d) with ventilation grids closed.

Noise emission is mainly related to the transmission through the ventilation grids, but the contribution from the hits of the coffee beans during grinding, along with some of the broadband vibrations around 1 kHz, is also transmitted to the upper panel through structural pathways (see Figure 13).

6. CONCLUSIONS

In this research, a methodology for vibroacoustic characterisation of household appliances is described. The use of standard sound pressure and sound level measurements, supported by noise source localisation techniques such as beamforming and sound intensity measurements, is shown to provide a comprehensive characterisation of the tested product. These experimental techniques also allow for the design of a dedicated setup in which, thanks to sound pressure and acceleration measurements, it is possible to identify the main noise and vibration transmission paths. The methodology is applied to a test case with the aim of characterising the vibroacoustic behaviour of a household coffee machine. The analysis shows that acoustic leakages, due to the presence of ventilation grids, may result in a significant impact on the overall noise emission. However, through combined noise and vibration analyses, a critical structural transmission path has also been identified. The results of these experiments highlight several key aspects of the product that can be optimized to reduce overall noise emission. The experimental techniques presented in this article can be adopted for the identification of potential mitigation measures for the noise generated by any kind of household appliance, or can be used for the definition of guidelines for an acoustically oriented design of new products.

7. ACKNOWLEDGMENTS

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