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ACOUSTIC ASSESSMENT AND IMPROVEMENT OF WOODEN ENCLOSURES USED IN MODERN KITCHENS FOR BUILT-IN HOUSEHOLD APPLIANCES

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Abstract

In modern and stylish kitchens, most of the time, a so-called built-in household appliance is enclosed in wooden furniture to enhance aesthetic attribute and elegance. These housings are impacting the sound and vibration of the household appliance itself, to the extent that was not studied before. Like any other enclosure for a sound source, the impact could be used for shaping of sound pressure level and perceived sound quality. At the same time, the sound emission of household appliances has been improved significantly by manufacturers over recent years, reaching noise floor levels [2], notably for refrigerators and dishwashers. This study is devoted to the acoustics of wooden enclosures, aiming at understanding their strengths and weaknesses in terms of contribution to overall appliance sound output. The experiments consist of placing omnidirectional speakers inside the enclosures and testing, with selected microphones, the amount of acoustic energy that traveled outside. At the end, some concepts with typical and novel materials were tested attempting an improvement of overall sound insertion loss.

Keywords: *household appliances, wooden enclosures, omnidirectional speaker, kitchen acoustics, sound insertion loss*

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1. Background

In modern kitchens, built-in household appliances such as refrigerators, dishwashers, washing machines, and ovens are widely used. Their integration into wooden kitchen furniture provides a visually consistent and aesthetically pleasing design.
Built-in kitchen furniture offers various material and finish options while maintaining standardized dimensions. Its general characteristics are also specified in the IEC 60704 series for household appliance noise measurements [1]. Although primarily designed for aesthetic and functional purposes, wooden enclosures may also influence the sound radiation of the enclosed appliance.

In recent years, manufacturers have significantly reduced the noise emitted by household appliances, particularly under standardized operating conditions [2]. However, appliances operating under high-load conditions, such as dishwashers during intensive washing cycles or refrigerators cooling warm food, can still generate clearly audible noise. This leaves room for further acoustic improvements beyond standardized noise ratings. Optimizing the acoustic performance of wooden enclosures therefore represents an additional opportunity to reduce appliance noise in everyday use.

2. Methodology

Two built-in household appliances, a dishwasher and a refrigerator, together with their corresponding wooden enclosures, were investigated in this study (Figure 1). The dishwasher enclosure represents a partially open design with an open front for appliance installation, whereas the refrigerator enclosure is nearly closed except for ventilation openings. These configurations represent two common installation concepts with substantially different acoustic boundary conditions.

Figure 1. Investigated built-in kitchen enclosures: dishwasher enclosure (left) and refrigerator enclosure (right).

To evaluate the acoustic attenuation provided by both the appliance structure and the surrounding wooden enclosure, an omnidirectional sound source was placed inside the appliance, inside the wooden enclosure alone, or inside the complete appliance–enclosure assembly.

Two compact omnidirectional loudspeakers manufactured by NTEK were used: the OMNI 4” LT (diameter: 280 mm) [3] and the OMNI 2” XS (diameter: 200 mm) [4] (Figure 2). Both loudspeakers provide broadband sound power levels exceeding 110 dBA over a frequency range from a few hundred hertz to 10 kHz, making them suitable for household appliance measurements.

Figure 2. Two sizes of omnidirectional speaker used in the study: 280 mm (left) and 200 mm (right).

The experimental campaign investigated the effects of loudspeaker type, appliance presence, enclosure type, and additional acoustic treatments. A fractional factorial Design of Experiments (DOE) was employed to evaluate these factors efficiently while minimizing the number of measurements. The design included blocking, randomized run order, and repeated measurements. The estimated test–retest uncertainty was ±0.25 dBA (99% confidence level). Statistical analysis was performed using Minitab; detailed statistical results are omitted because of space limitations.

3. Measurements

The omnidirectional sound source was positioned at the geometric center of the investigated configuration (Figure 3). The complete test setup was placed inside an anechoic chamber to eliminate reflections and external acoustic interference. During all measurements, the household appliances remained switched off and served solely as physical barriers affecting sound propagation, while the power amplifier was placed on the floor inside the investigated configuration.

For all measurements, the amplifier gain was kept constant to ensure repeatability. Whenever possible, enclosure doors were kept closed, and reference measurements of the loudspeaker were performed prior to its installation inside the investigated configuration.

Figure 3. Positioning of the omnidirectional sound source within the investigated configurations.

Three microphones were positioned 1 m from the investigated configuration, located in front of, beside, and above the setup to characterize the radiated sound field. For the refrigerator configuration, the upper microphone position was omitted because of insufficient clearance to the anechoic chamber ceiling.

White and pink noise signals were recorded using the HEAD acoustics SQuadriga measurement system. Audio recordings were additionally acquired for post processing and comparative analysis. Signal processing was performed in Artemis.

4. Analysis & Discussion

Table 1 illustrates the influence of the investigated wooden enclosures on the radiated sound field. For the partially open dishwasher enclosure, the sound pressure level measured at the front microphone was approximately 9 dBA higher than at the side microphone. In contrast, the nearly closed refrigerator enclosure exhibited a much smaller front-to-side difference of approximately 3 dBA.

Table 1. Measured sound pressure levels at the front and side microphone positions for selected enclosure configurations

Configuration Mic position	Front Mic. SPL (dBA)	Side Mic SPL (dBA)
Large speaker Dish. enclosure	92.1	83.0
Small speaker, no enclosure	86.9	84.9
Small speaker, Ref. enclosure	78.7	75.8
Large speaker, no enclosure	91.4	90.8

These observations demonstrate that wooden enclosures can significantly modify the radiated sound field around the appliance. However, conventional sound power measurements according to IEC 60704 [1] are based on spatial averaging over multiple microphone positions (typically six, eight, or ten). As a result, directional effects introduced by the enclosure may not be fully reflected in the resulting single sound power level.
The experimental investigation was conducted in two stages. First, the acoustic performance of the original configurations was evaluated. Subsequently, several passive treatments were investigated to improve enclosure performance.

4.1 Baseline acoustic performance

As a reference, the attenuation provided by the household appliances themselves was first quantified. The largest sound pressure level reduction was achieved when the omnidirectional source was placed inside the household appliance, reaching approximately 20–30 dBA for the dishwasher configuration (Block 1, Figure 4) and approximately 15 dBA for the refrigerator configuration (Block 2, Figure 4). These results demonstrate that modern household appliances already provide substantial acoustic attenuation through their structural and NVH design.

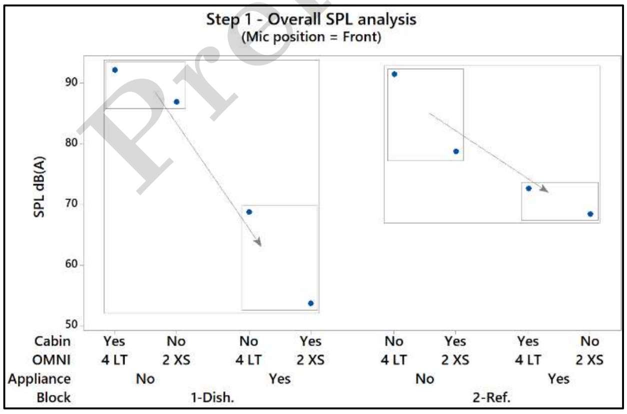

Figure 4. Frontal microphone overall sound pressure level attenuation for the investigated baseline configurations.

The attenuation was observed consistently at both front and side microphone positions (Figures 4 and 5) and was broadband in nature, extending above 300 Hz for the dishwasher configuration and above 500 Hz for the refrigerator configuration (Figure 6).

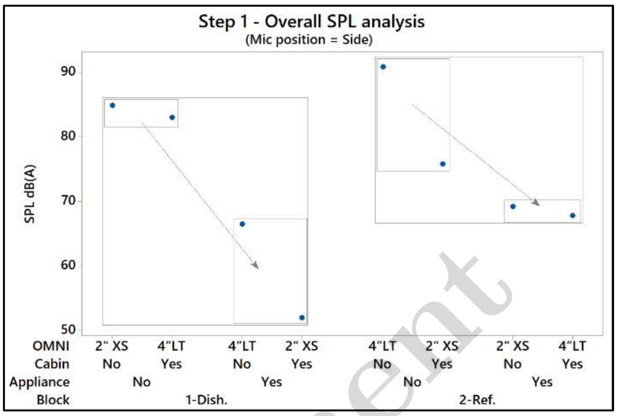

Figure 5. Lateral microphone overall sound pressure level attenuation for the investigated baseline configurations.

These frequency ranges partially coincide with some of the most characteristic appliance noise sources, namely fan noise in refrigerators and water-flow noise in dishwashers.

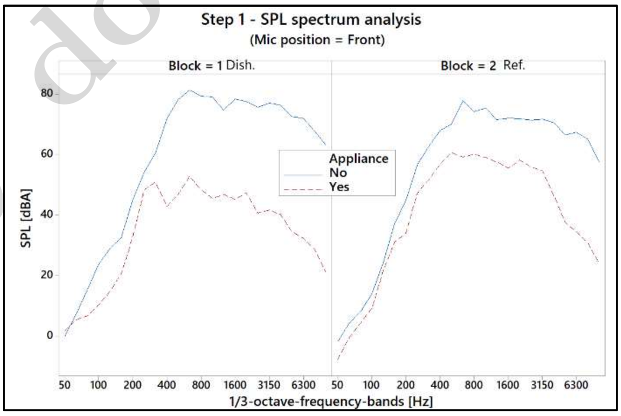

Figure 6. Frequency-dependent sound pressure level attenuation for the investigated configurations and frontal mic: dishwasher (left) and refrigerator (right).

In contrast, the influence of the wooden enclosure alone depended strongly on both the enclosure design and microphone position. For the dishwasher enclosure, the effect was negligible at the front microphone position, but reached approximately 8 dBA of overall SPL, when the side microphone was considered, whereas the refrigerator enclosure produced a more uniform attenuation of approximately 8 dBA for both microphone positions, particularly above 200 Hz (Figure 7).

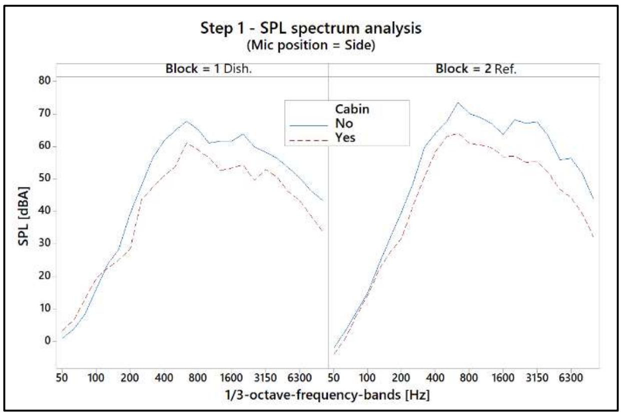

Figure 7. Frequency-dependent sound pressure level attenuation for the investigated configurations and lateral mic: dishwasher (left) and refrigerator (right).

The observed differences are likely related to the structural and vibroacoustic properties of the investigated appliances. The dishwasher incorporates additional NVH-related components, including bitumen layers, fibrous insulation, and a steel tub, resulting in greater sound attenuation than the refrigerator. Furthermore, the appliance structures behave as nearly closed acoustic volumes, whereas the surrounding wooden enclosures remain partially open because of the open dishwasher front and the ventilation openings required for the refrigerator enclosure. Nevertheless, the surrounding walls of the refrigerator enclosure still provide noticeable sound attenuation.
For the remainder of tests, the smaller OMNI 2 XS was selected because of its compact dimensions. Psychoacoustic metrics such as Loudness and Sharpness were analyzed, but are not displayed here because the observed trends were consistent with the sound pressure level results.

4.2 Evaluation of passive acoustic treatments

Additional passive acoustic treatments were investigated to improve the acoustic performance of the wooden enclosures. The dishwasher and refrigerator enclosures were evaluated using three treatment concepts: a conventional porous absorber, a panel absorber (Distributed Mode Absorber, DMA) made of furniture materials similar to the structures in [5], a DMA with a T-shaped cut-out resonator [6], and a bitumen layer with an areal density of approximately 3.5 kg/m² (Figure 8).

Figure 8. Investigated passive acoustic treatments applied to the wooden enclosures: DMA (top left), bitumen (top right) and porous absorber (bottom).

The investigated uniform DMA, comprising a 0.6 mm Continuous Pressure Laminate (CPL) front panel and a 12 mm back cavity, demonstrated only narrow-band attenuation, reaching up to 10 dB around its resonance frequency (Figure 9). On the other hand, DMA with cut-out (that has Plexiglas 1.86 mm front panel a 12 mm back cavity) provides slightly better results around 12 dB decrease in maximum for 250-300 Hz region. This shows that the operating principle of the panel absorber was not fully activated under the acoustic conditions and limited geometries (effect not visible in overall SPL from all directions). For some of the typical noise problems in household appliances however (tonal sounds from ventilation system, or motor for example), it can become a useful engineering tool to tackle sound quality or perception problems.

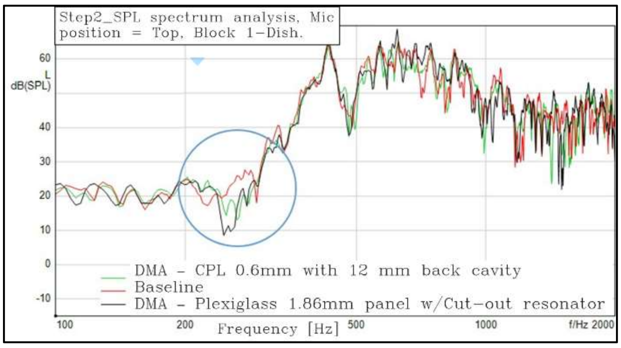

Figure 9. Effect of the DMA panel absorber on dishwasher enclosure sound pressure level attenuation.

Similarly, the application of bitumen layers resulted in only a limited improvement of approximately 0.5–1.0 dB of overall SPL and 1-2 dB systematically in frequencies above 1000 Hz, mainly for the refrigerator enclosure. Refrigerator's wooden enclosure allowed for the greater bitumen-covered surface area than dishwasher's, still the effect measured is relatively small. This limited improvement is consistent with the primary function of bitumen as a damping treatment for structure-borne vibrations, whereas the present measurements were dominated by airborne sound radiation from the omnidirectional source. Overall, both treatment concepts provided only limited acoustic benefits.

In contrast, the conventional porous absorber yielded substantially greater attenuation than the other investigated treatments (Figure 10).

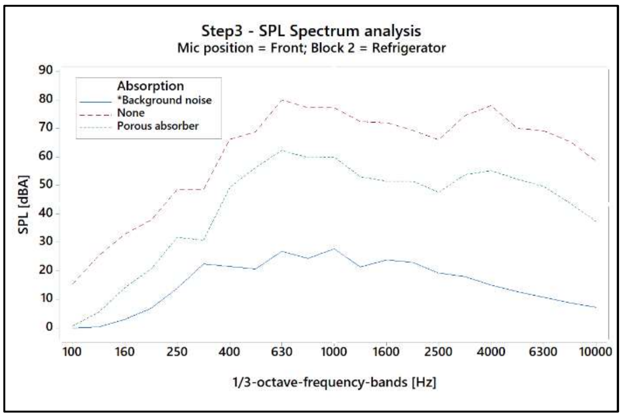

Figure 10. Effect of the conventional porous absorber on sound pressure level attenuation.

Although the achieved reduction remained below the attenuation already provided by the household appliance itself, sound pressure level reductions approaching 10 dBA were obtained, primarily above 500 Hz, when the absorber was properly positioned and the enclosure doors were closed. The main limitation of this approach is the additional installation volume required by the porous absorber. Compact metamaterial-based absorptive structures may offer comparable acoustic benefits with a smaller footprint.

5. Conclusions

The present study investigated the influence of wooden enclosures and additional passive acoustic treatments on sound propagation and sound pressure level reduction in built-in household appliance configurations. The results confirmed that both the appliance structure and the surrounding wooden enclosure significantly influence the radiated sound field, affecting not only the overall sound pressure level but also its directivity.

The largest attenuation was provided by the household appliances themselves, when the omnidirectional sound source was positioned inside the appliance, reaching approximately 20–30 dBA for the dishwasher and approximately 15 dBA for the refrigerator. These effects were observed consistently across microphones and within frequency ranges representative of typical appliance noise sources. These results demonstrate the high level of acoustic optimization already achieved through appliance design. Nevertheless, the surrounding wooden enclosure provided additional attenuation, with its effectiveness strongly depending on enclosure geometry. The nearly closed refrigerator enclosure exhibited a more uniform attenuation than the partially open dishwasher enclosure.

Among the investigated passive treatments, the conventional porous absorber provided the greatest additional sound reduction, approaching 10 dBA above 500 Hz when properly positioned and combined with closed enclosure doors. In contrast, the investigated panel absorbers (DMA) and additional bitumen layers produced only limited improvements under the investigated conditions. The results indicate that enclosure openness, acoustic confinement, and the available absorber volume are the dominant factors governing enclosure performance.

The work also demonstrated that conventional sound power level measurements based on spatial averaging may not fully capture directional acoustic effects introduced by furniture enclosures. Future studies should therefore focus on directional sound field analysis and on development of compact low-volume absorptive or metamaterial-based solutions suitable for practical kitchen appliance integration.

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