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IDENTIFICATION OF CRACK NOISES IN HOUSEHOLD REFRIGERATORS

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Abstract. *This paper presents a new visualization method of complex sound sources in combined fridge freezers. Measurement method with sixty array microphones in free sound field conditions is used. Laboratory acoustic measurements using an algorithm of the complex sound sources visualization are performed. With this method, sound effects are successfully identified, localized and calculated. The individual crack noises emitted as a result of thermal dilatation of different types of material in the transitional cooling modes of the household refrigerator.*

Key words: *free field, array microphones, acoustic measurements, crack noises*

1. INTRODUCTION

The first step to a successful noise reduction is the noise source identification (NSI). In this process, we can get assistance from the systems which visually place the sources of noise in the room [1].

In case using one sensor (microphone or p-p probe) which measures sound pressure or sound intensity, we can determine the source of noise only by executing several measurements in different locations in the room and process the results numerically. When we deal with time-varying noise, the single sensor approach is not satisfactory.

In such case, a microphone array must be used for sound capture. All methods of processing thus captured (acoustic) signals have been known among the professionals under the term 'acoustic holography'. The microphone array has been known as 'acoustic holographic camera'.

Refrigerators and freezers perform their function continuously, therefore it is important that their operation is as silent as possible and that they emit minimal noise. Their users perceive these features as on of the main criteria for the quality of appliances

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[9, 10]. Therefore, in addition to the declared sound power level of the appliances indicated on their energy label, the quality of the emitted noise is also important [11].

An additional issue is represented by the fact that refrigerators and freezers are becoming increasingly more complex. In addition to compressors, which have always been one of the main sources of noise, there is an increasingly frequent use of coolant directing valves, fans, air dampers, automatic ice makers and other components, the operation of which additionally contributes to the total noise level of refrigerators and freezers.

The noise level of refrigerators and freezers is also influenced by the type of the cooling system. One of the loudest is the so-called No Frost cooling system, which comprises the majority of the previously mentioned components. In such a cooling system, loud crack noises can also occur, which can be very annoying for the users, particularly during the night time. Although the crack noises occur in appliances made by different manufacturers, not much research in this field can be found in literature [12, 13].

Due to the short duration of sound impulses, conventional approaches and methods were not sufficient to solve these problems; we had to use a new method of visualization of complex sound sources. It is a measuring method using an array of sixty microphones in free sound field conditions. With this method, we successfully identified, localized and calculated the sound power level of the individual sound impulses, which helped us in determine the causes and searching for the solutions to eliminate crack noises. At the same time, we used it for a quantitative comparison of the baseline and improved the configuration of the appliances, which is presented in more detail in the text below.

2. Building Blocks of the Acoustic Holography System

The system is composed of four basic building blocks:

- Non-uniform array of 60 microphones, 96 cm x 96 cm in size, with an optical camera in the center. The microphones are B&K Type 4957, the distance between the microphones ranges from 10 to 15 cm. A USB camera is installed - uEye model made by IDS Imaging Development Systems GmbH from Germany;
- A sampler: 5 modules B&K Type 3053-B-12/0 in the housing B&K Type 3660-C-000;
- Signal capture program B&K Pulse LabShop, version 20.0.0.455, and
- Signal processing program B&K Array Acoustics Post-processing, version 20.0.0.455.

The size of the used microphones (B&K 4957) is ¼ inch. Their frequency range is from 50 Hz to 10 kHz, dynamic range is from 32 to 134 dB. Their sensitivity is 11.2 mV/Pa. They have an integrated preamplifier which supports the TEDS protocol [3] (the microphone's characteristics are saved in the microphone and can be transferred to the sampler).

The measuring field with an optical camera in the center (Figure 1, left side) allows the results of measurements and calculations to be loaded on the image of the measured object. The sampler used (B&K 3053-B-12/0) supports 12 channels and has the frequency range up to 25.6 kHz. It is adapted for CCLD-microphones. The client communicates with it using the LAN-Xi protocol [4]. A system for 60 microphones requires 5 such modules installed in the housing B&K 3660-C-000 (Figure 1, right side. The latter also contains a suitable power supply unit and a LAN-Xi connection concentrator. The program B&K Array Acoustics Post-Processing is used for indirect analysis of captured signals. The basic version supports three methods of processing (licences for several other methods can be purchased additionally);

- delay and sum beamforming (DAS),
- SONAH, and
- wideband holography.

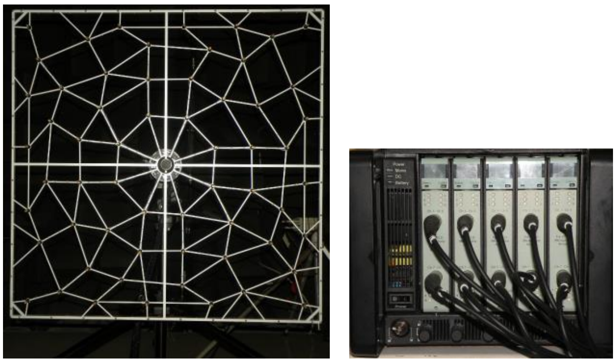

Fig. 1 Brüel & Kjær system for acoustic holography, microphone array (left side), and sampler (right side)

All methods calculate the sound pressure or the intensity for a virtual plane in space (calculation plane). All planes are parallel to the microphone array. For each measurement, any number of such planes can be set. The density of points on the calculation plane depends on the setting - the default distribution is a 2 cm grid.

The delay and sum beamforming method [5] is more accurate at higher frequencies. For each point on the selected plane, the delay of the sound to each microphone is calculated first, and then the appropriately delayed signals from all microphones are summed together. The calculation is repeated for all points on the monitored plane.

The SONAH method (Statistically Optimized Nearfield Acoustic Holography) [6] is based on the calculation of phase lag in the near acoustic field. During measuring, the microphone array must be in the immediate vicinity of the object being measured. The highest frequency that can be processed by this method depends on the maximum distance between the microphones in the array. For the array used, it amounts to 1113 Hz.

The wideband holography method [7] combines good characteristics of both above-mentioned methods - it has a good resolution at low and high frequency, but is the most demanding in terms of calculation.

3. Crack Noises In Household Refrigerators and Freezers

The wideband holography method [7] combines good characteristics of both above-mentioned methods - it has a good resolution at low and high frequency, but is the most demanding in terms of calculation.

Problems with cracking noise were occurring particularly in appliances with the No Frost cooling system. In domestic refrigeration and freezing appliances, the prevailing cooling systems are those with the compressor technology. Such cooling systems consist of at least the following closed-system components: the compressor which supplies work into the cooling system, the condenser which emits heat into the environment; the capillary tube which lowers the coolant pressure, and the evaporator which extracts heat from within the refrigerated space.

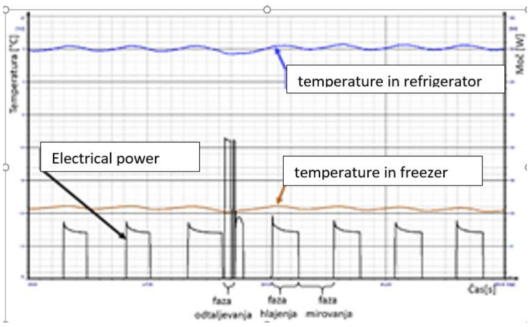

Fig. 2 Temperature oscillation in refrigeration and freezing appliances

A cooling system operates periodically; when the temperature inside the refrigerated space rises above a certain temperature, the cooling system turns on (start of the cooling phase), wherein the temperatures in the evaporator area sink below 0°C, which is followed by extraction of heat from refrigerated spaces by means of natural or forced convection. As soon as the temperature inside the refrigerated space sinks below a certain temperature, the cooling system turns off (start of the standstill phase). By alternating the cooling and standstill phases, the temperature in the refrigerated space oscillates around the set value, as shown in Figure 2.

Fig. 3 Rime and clear ice on the evaporator

During the cooling phases, moisture is released from the cooled air in the evaporator area and deposited in the form of rime and clear ice on the surfaces of the evaporator and the neighbouring parts (Fig. 3). Accumulation of rime and clear ice reduces the efficiency of the cooling system; therefore, defrosting is required. In addition to manual defrosting, there are two automatic methods of evaporator defrosting:

1. Auto Defrost - passive method without heating devices in the evaporator area used mainly in refrigeration compartments,
2. No Frost - active method with additional heaters in the evaporator area, used mainly in freezing compartments and occasionally in refrigeration compartments.

In the Auto Defrost passive method, the temperature in the evaporator area rises above 0°C during each standstill phase of the cooling system, causing the rime and clear ice accumulated on the evaporator to melt and drain from the refrigerated space. In this defrosting method, the defrosting cycles take place during each standstill phase.

In cooling systems with the active No Frost defrosting method, the temperature in the evaporator area does not usually rise above 0°C during the standstill phases of the cooling system; therefore, in each subsequent cooling phase, an additional layer of rime and clear ice is deposited in the evaporator area. Defrosting takes place in provided defrosting cycles. During these cycles, heaters mounted on the evaporator are switched on and heat up the evaporator area. Each defrosting cycle lasts until the prescribed temperature above 0°C is reached in the evaporator area, which ensures that the accumulated rime and clear ice will melt and drain from the refrigerated space.

Fig. 4 Frozen droplets on the cell

At the end of each defrost cycle (in both passive and active defrost mode), water droplets of different sizes remain of the surfaces of the evaporator and surrounding parts; in the next working cycle of the cooling system, they freeze and turn into ice droplets. Figure 4 shows frozen droplets on the cell behind the vaporizer.

4. Localization and Evaluation of Crack Noise Occurrence

The search for causes mostly took place in the semi-anechoic chamber of the Acoustics and Vibration Laboratory (Fig. 5), where we established the point of origin of the occurrences of crack noises and evaluated them.

Fig. 5 Measurements by means of the SONAH technique

For this purpose, we used a technique which is a combination of Nearfield Acoustic Holography (NAH) and Beamformimg (BF), and named Statistically Optimized Nearfield Holography – SONAH [14].

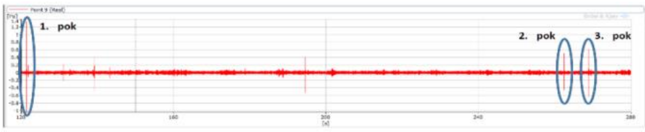

Fig. 6 Time course of the sound emitted by the refrigerator in the first set of measurements

Measurements of the emitted noise were carried out in two sets, i.e.:

- the first set - in the defrosting phase,
- the second set - after the defrosting phase, during the operation of the compressor.

In the first set, more crack noises were measured; an example of measurement is shown in Figure 6. In this case, we selected the three marked crack noises. Figure 7 shows their total sound power in the frequency range 125 Hz - 4000 Hz. Disregarding the first crack noise which shows non-characteristic behaviour (the length of the signal is much longer that in all other cases, and the sound power is significantly lower than in the case of the second and third crack noise), we were able to establish that in both the second and the third crack noise, the majority of the source is in the location of the evaporator marked with number 2 in Figure 7.

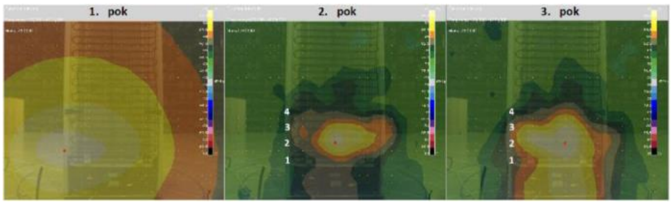

Fig. 7 Total sound power of the three selected crack noises - sound images are not in scale

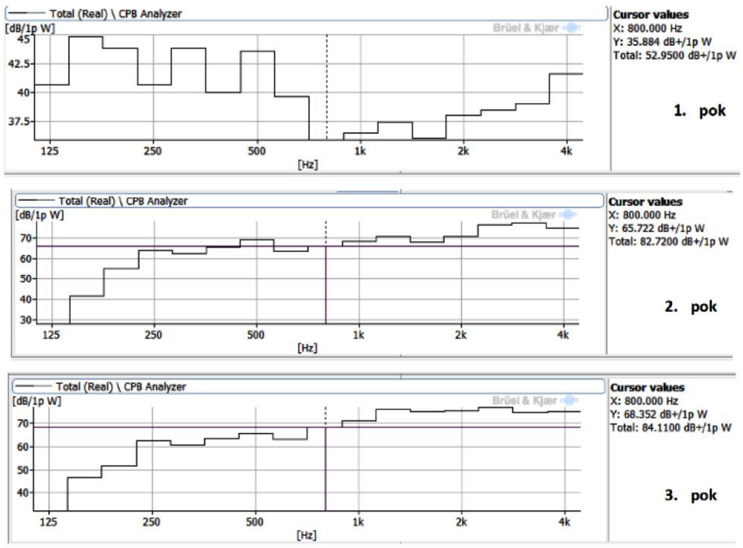

Fig. 8 Frequency spectrum of the selected crack noises 125 Hz – 4000 Hz

The analysis of sound power by individual thirds (Fig. 8) showed that the total sound power in the case of the first crack noise is 53 dB, in the case of the second crack noise, 83 dB, and in the case of the third crack noise, 84 dB. In the frequency spectrum of the second and the third crack noise, there are no significant differences; the majority of the sound power above 70 dB was from the frequency range between 1000 and 4000 Hz.

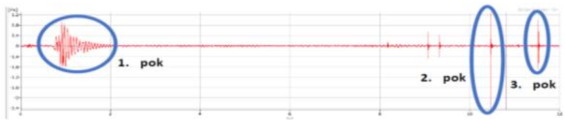

Fig. 9 Time course of the second set of measurements

In the second set, several crack noises were measured as well. For the analysis, we selected 3 crack noises (marked in Figure 9). Figure 10 shows the total sound power in the frequency range 125 Hz - 4000 Hz for the example of all three crack noises from the second set of measurements. It is evident from this Figure that in the first crack noise, the main source of noise is in the area marked with numbers 2 and 3, and in the second and the third crack noise, the main source of noise had shifted to the right and upwards, so that the main source of noise was in the area marked with number 4. Both established sources of the main noise are in the area of the evaporator.

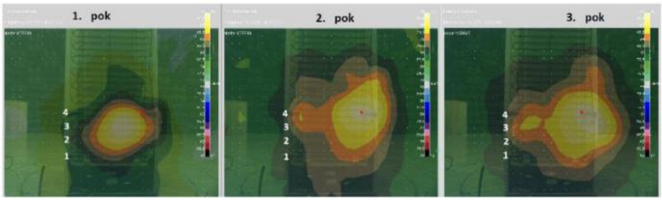

Fig. 10 Total sound power of the three selected crack noises - sound images are not in scale

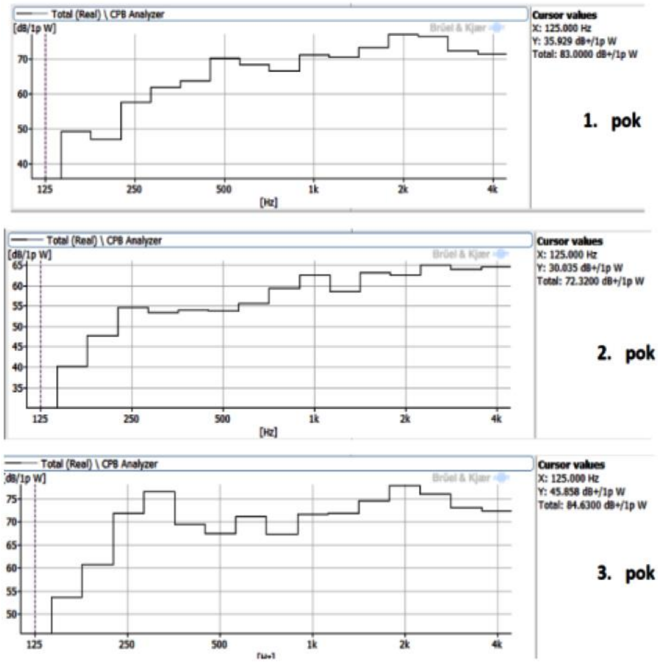

Fig. 11 The frequency spectrum of the selected crack noises of the second set of measurements 125 Hz – 4000 Hz

The analysis of sound power by individual thirds (Fig. 11) showed that the total sound power in the case of the first crack noise is 83 dB, in the case of the second crack noise, 72 dB, and in the case of the third crack noise, 84 dB. Similarly, as in the first set of measurements, the majority of the sound power, which is above 70 dB, is concentrated in the higher frequency range above 1000 Hz.

Figure 12 shows the measurements of the total sound power (125 - 4000) for the first and the second set of measurements. The top three images show the measurements of the first set, and the bottom three images show the measurements of the second set of measurements. After comparing the results of measurements of both sets, we came to the conclusion that the maximum sound power in individual crack noises is comparable, i.e. approximately 83 dB. This result confirmed the fact that the crack noises are very loud and annoying. The difference occurring between the first and the second set is in the shift of the main source of the crack noise. In the case of the first set of measurements, the source appears on the position 2 (marked in Figure 10), while in the case of the second set of measurements, this source appears higher, at the position 3-4 (marked in Figure 12). Both established positions are in the area of the evaporator, as we already concluded in the first phase of searching for causes for occurrence of crack noises.

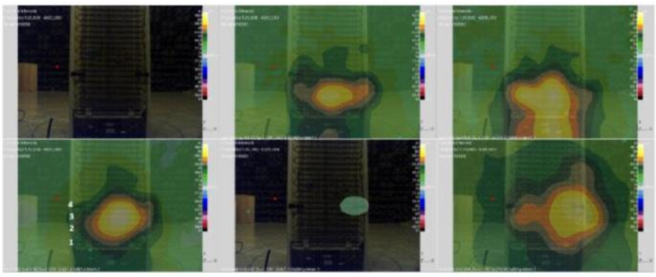

Fig. 12 Comparison of total sound power of all six crack noises, top - measurements from the first set, bottom - measurements from the second set. The figures are scaled to the highest measured sound power level of 84 dB.

5. Description of the Solution to the Problem

5.1. Analysis of causes for crack noises

Considering the knowledge of the conditions around the evaporators of No Frost appliances during and after the defrost cycle, and based on the above listed findings, we set up two hypotheses about the causes for occurrence of crack noises. At the end of each defrost cycle, water droplets of different sizes remain on the surfaces of the evaporator and surrounding parts; in the next working cycle of the cooling system, they freeze and turn into ice droplets.

Crack noises can be heard when these water droplets are turning into ice. According to the first hypothesis, they occur when the evaporator is relatively tightly surrounded by neighbouring parts (e.g. the cell and the air conveyor) from at least two opposite directions and when water droplets appear in the areas between the evaporator and at least one of the neighbouring parts, but when turning into ice droplets, they push the evaporator away from the said neighbouring part, If during this process, the tensions in the individual droplet exceed the burst tension of the ice, the latter bursts and vibrations in the form of an annoying crack noise occur.

According to the second hypothesis, the crack noises occur when the evaporator is in the vicinity of at least one part (e.g. the cell or the air conveyor) with a different temperature coefficient of length expansion, which can, upon change of the temperatures of the evaporator and the neighbouring parts, and due to different thermal dilatations, cause tensions in ice droplets in the intermediate zone, which exceed the burst tension of the ice, causing the droplets to burst, resulting in vibrations in the form of annoying crack noises.

Hence, both hypotheses speak of the occurrence of vibrations due to bursting of ice droplets, which in themselves would not be so loud if the vibrations were not transferred to the insulated housing of the appliances. Due to relatively low density and high rigidity of the insulation of these housings, the vibrations are very well transferred and their sound effect can even be amplified.

Considering the above findings and hypotheses, we tested a series of versions of design improvements and operation algorithms, with which we tried to reduce the frequency and lower the loudness level of crack noises in refrigerators and freezers. Each of the improvements was evaluated by means of subjective identification, i.e. with the number and volume of crack noises during the monitored period.

5.2. Results of measurements of refrigerators' noise with structure modification

Considering the above findings and hypotheses, we tested a series of versions of design improvements and operation algorithms with which we tried to reduce the frequency and lower the loudness level of crack noises in refrigerators and freezers. Each of the improvements was evaluated by means of subjective identification, i.e. with the number and volume of crack noises during the monitored period.
A relatively simple procedure of placing aluminium foil between the evaporator and the evaporator cell proved to be the best solution.

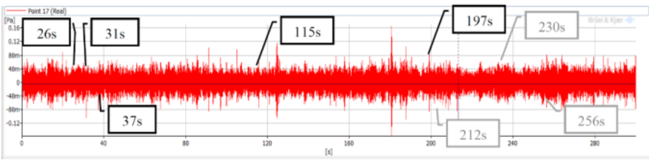

Fig. 13 Time course of the final configuration in the defrost phase

The same as in the case of the original configuration, the final solution was also evaluated by means of the combined SONAH technique. Figure 13 shows the sound pressure in the defrosting phase. Already from the comparison of time records of the sound pressure, we were able to establish that the sound pressure amplitude was decreased in case of all crack noises. Furthermore, the time of occurrence of individual crack noises could not be established on the basis of the sound recording; it could only be established by listening to the sound signal. Individual points in the time record, where the analysis of crack noises was carried out, are marked in Figure 13.

Here, it should be pointed out that the last three points were not analyzed, as the analysis of first points showed a minimum deviation, i.e. differences between individual crack noises.

The comparison of all five individual crack noises is shown in Table 1. As it is evident, the total sound power level of an individual crack noise does not exceed 44.6 dB (the latter occurs at 37 s).

Table 1 Sound power levels of crack noises in the defrost phase

Number of crack noises	Time of crack noises, s	Total sound power, dB
1	26	38.9
2	31	40.1
3	37	44.6
4	115	38.8
5	197	39.7

Figure 14 shows the locations of the source upon the occurrence of the crack noise for the example of all five analysed crack noises. The sixth figure (right side, bottom) presents the analysis of operation of the refrigerator in the first 20 seconds of operation. All figures are scaled to the highest measured sound power level (44.6 dB).

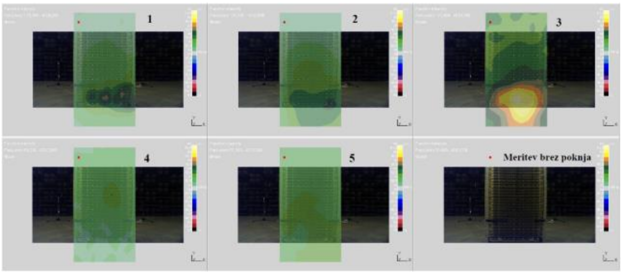

Fig. 14 Comparison of total sound power level of all five crack noises in the defrost phase

The same procedure of evaluation of crack noises was used for the post-defrost phase, with the operation of the compressor (Figure 15). Similarly, the difference between the operation of the refrigerator and crack noises in this phase was so small that the occurrence of crack noises was impossible to determine from the time measurements of the sound pressure. In Figure 15, the individual crack noises are marked, but the last 5 crack noises were not analysed due to the above-described causes. As evident from Table 2, the total sound power level does not exceed 41.14 dB (at 28 s).

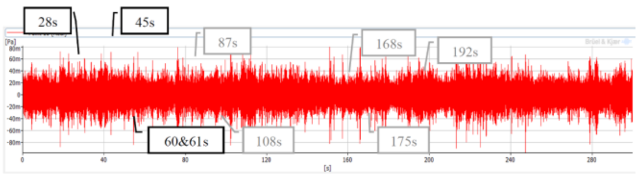

Fig. 15 Time course of the final configuration after the defrost phase

Figure 16 shows the locations of the source upon the occurrence of the crack noise for the example of all five analysed examples. The fourth figure (right side) presents the analysis in the first 20 seconds of operation of the refrigerator. All figures are scaled to the highest measured sound power level (41.1 dB).

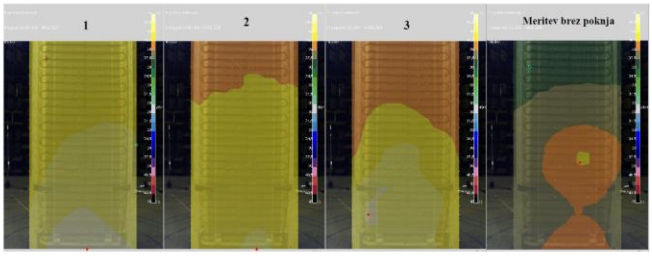

Fig. 16 Comparison of total sound power level of all three crack noises after the defrost phase.

Table 2 Sound power levels of crack noises after the defrost phase

Number of crack noises	Time of crack noises, s	Total sound power, dB
1	28	41.1
2	45	40.0
3	60&61	40.4

6. Conclusion

The main sources of noise in refrigerators and freezers, such as compressors, fans or circulation of coolant, can be identified relatively well and evaluated by using conventional measurement methods. We have been using them for years, both in development measurements, which helped us in the search for the lowest possible noise level in the appliances, and in the execution of standard measurements, based on which the declarations of noise levels of appliances are determined. The noise from these sources has also been discussed in a number of scientific papers, where guidelines are provided which can be taken into consideration already in the phase of development of the appliances as well as in the process of eliminating problems on the market.

However, acoustic phenomena occurring during the operation of refrigerators and freezers are discussed and measured less frequently. This was also the reason to present an example of successful application of modern measuring equipment used to visualize sound sources in transient phenomena which were reflected in the form of annoying crack noises. With its help, we managed to decrease the sound power level of crack noises from the original level of 84 dB to the final solution of 45 dB. By presenting this case, we are trying to encourage more frequent use of this equipment for more efficient and effective remedying of such deficiencies in the appliances.

Furthermore, we presented in the article the combination of the use of this equipment and the subjective evaluation of noise, and we tried to demonstrate the need for combining different approaches to efficiently and effectively solve such challenges. The subjective method of identification of less common sounds, e.g. in the form of monitoring the operation of appliances in offices and homes, and recording extraordinary events, must be used in the earliest possible phase of development of the appliances. By doing so, the majority of deficiencies can be identified in early phases rather than after launching the appliances to the market.

With the complementary use of various methods and equipment as well as the cooperation of both Gorenje's domestic and external experts, we can meet the users' expectations, and at the same time, with lower noise level declarations, we contribute to competitive advantages of our appliances.

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IDENTIFIKACIJA ZVUČNIH IMPULSA KOD FRIŽIDERA ZA UPOTREBU U DOMAĆINSTVU

U članku su predstavljene nove metode vizualizacije kompleksnih zvučnih izvora kod kombinovanog frižidera. Upotrebljena je metoda merenja sa matricom šezdeset mikrofona u uslovima prostog zvučnog polja. Izvedena merenja u akustičnoj laboratoriji koriste algoritam koji omogućava vizualizaciju kompleksnih zvučnih izvora. Sa tom metodom smo uspešno identifikovali, lokalizovali i izračunali zvučnu snagu zvučnih impulsa emitovanih kao posledica temperaturnih diletacija različitih vrsta materijala u prelaznom režimu hlađenja kod aparata za kućnu upotrebu.

Ključne reči*: prosto zvučno polje, mikrofonska matrica, akustična merenja, zvučni impulsi*