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Identification of crack noises in household refrigerators

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Abstract

The crack noises propagating from a refrigerator disturb residents in a household; however, the reasons behind the mechanisms of such noises have not been identified yet. In this study, the crack noises in modern household refrigerators are identified and their root causes are explored. The appropriate parameters for overall and Fourier analyses are first determined and the noise characteristics of typical household refrigerators under various conditions are presented. Then, a special test rig providing remote control of the subcomponents including the compressor, fan and heater is designed and structural acceleration and sound pressure measurements inside and outside the test rig in a quiet room are performed. The acoustic and vibration measurements are conducted under various conditions by separately controlling each subcomponent. The crack noises in typical household refrigerators are identified and their root causes are explored by using the results of the overall and Fourier analyses. Some solutions to minimize the crack noises in household refrigerators are also summarized.

Keywords: Crack noise; household refrigerator; overall analysis; frequency spectrum; temperature change.

1. Introduction

Vibration and acoustic behavior of domestic appliances are becoming increasingly more important as these commodities are linked with life quality and customer satisfaction [1-4]. Furthermore, noise and vibration levels perceived by consumers are frequently recognized as a measure of overall quality of domestic appliances [1-2, 5]. Unlike other home appliances, refrigerators operate all day and users respond sensitively to the noise they generate. It is reported that more than half of the inhabitants are annoyed by refrigerator noise [5]. The inhabitants are more annoyed with the unsteady fluctuating noises as compared to the steady operating noise [1-3, 5-6]. It should be noted that the impulsive type noises are common in modern refrigerator models [7-8] and such crack noises affect the sound quality of the product [8-11]. Especially, during sleeping hours due to natural decrease of the background noise, the noise emitted by a refrigerator could be very annoying.

There are many studies on the main noise sources of refrigerators such as compressor [12] and fans [13] and operating phases of a refrigerator such as start-up, steady state and ending [2]. Identification and quantification of the compressor and fan noises is relatively straightforward as the positions and the properties such as rotation speeds, and number of blades of these components are known and the exact contributions of these components can be identified by using the frequency spectrums measured by operating each component separately. However, the crack noises, a serious problem of today's no-frost (modern) refrigerators, have not been identified and the root causes of such noises have not been explored in the literature [13-15]. This paper attempts to fill this void with a controlled experimental study and by analyzing a huge number of structural acceleration and sound pressure measurements conducted in a quiet room (representing a kitchen of a typical house) using a few refrigerators and a special test rig under various conditions. Based on the main findings, some solutions to minimize the crack noises in household refrigerators are also summarized.

2. Problem formulation

The exact components (or subcomponents) propagating the crack noises in household refrigerators are not known although the crack noises can be heard by ear and measured by a microphone outside a refrigerator in practical measurements. Furthermore, the reasons behind the mechanisms of such burst type noises are not well known. The noise characteristics including the crack noises in household refrigerators are first presented to reveal the existing state. Then, a special test rig providing remote and separate control of each subcomponent (i.e., the compressor, fan and heater) is designed to identify the crack noises in household refrigerators. The unnecessary components (or parts) creating difficulty to identify the crack noises with good reliability are excluded from the test rig designed here. The test rig includes mainly half of a refrigerator airframe, a compressor, a fan, a heater, an evaporator and cooling pipes. The schematic of the test rig including the subcomponents is shown in Fig. 1. Both structural acceleration and sound pressures are measured inside and outside the test rig in a quiet room representing a kitchen of a house. The temperature measurements on the surface of the heater are also conducted. The sensor positions where the measurements include structural acceleration (a), sound pressure (p) and temperature (T) are shown in Fig. 2 where a_1 , a_2 and a_3 are the acceleration levels measured on the heater, inside and outside panels, respectively, and p_1 , p_2 and p_3 are the sound pressures measured inside the cabinet and at some points close to the evaporator and compressor, respectively.

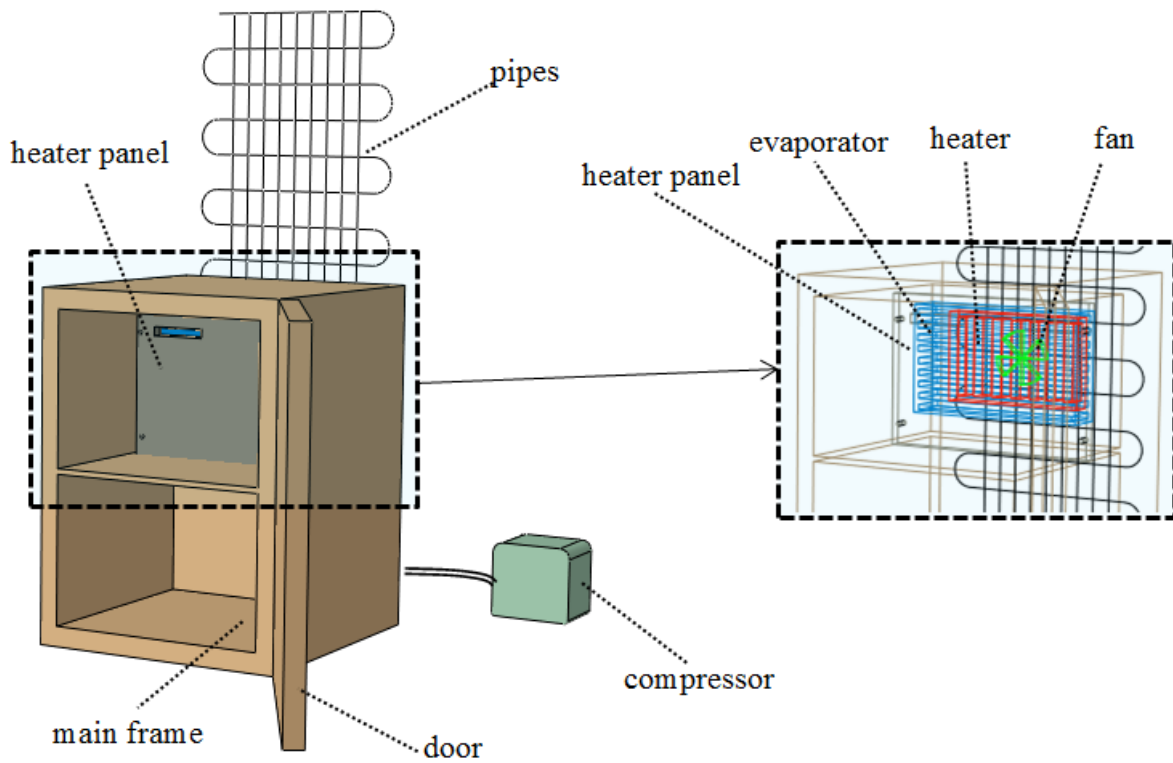


Fig. 1. The schematic of the test rig including the subcomponents.

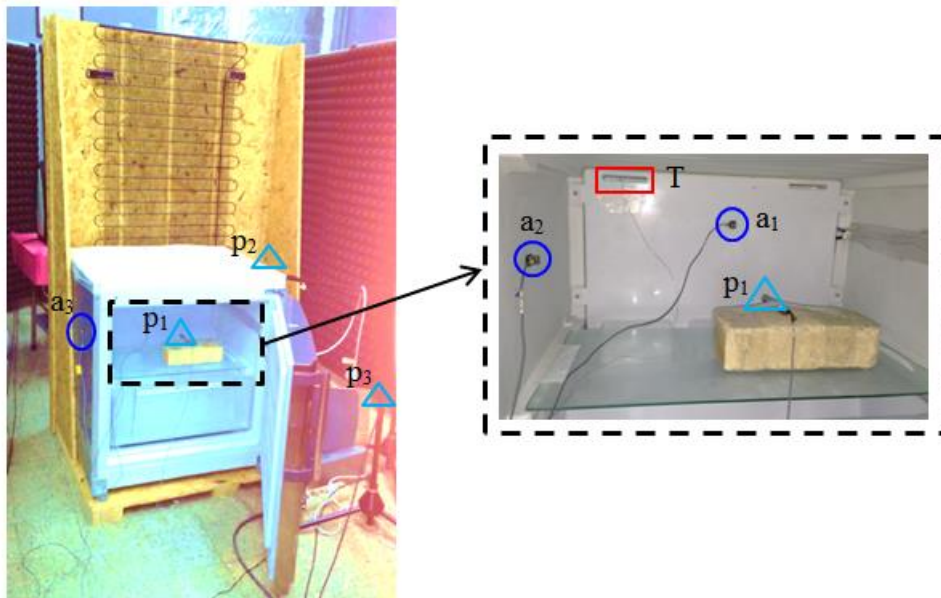


Fig. 2. Sensor positions where the measurements include structural acceleration (a), sound pressure (p) and temperature (T).

The time signals of both structural acceleration and sound pressure are first recorded with a high sampling rate ($f_s = 2^{15} = 32.8$ kHz) and the overall and Fourier analyses of the signals are performed as a post processing phase [16-17] later. The use of exponential averaging (i.e., the use of exponential time weighting) for continuous non-stationary signals is very common in acoustic measurements [18]. The overall value of a time domain sound pressure signal based on exponential averaging with time weighting τ at any time t is determined as follows:

$$p_\tau(t) = \sqrt{\frac{1}{\tau} \int_{-\infty}^t p^2(\xi) e^{-(t-\xi)/\tau} d\xi} \quad (1)$$

where $p(\xi)$ is the instantaneous time varying sound pressure and ξ is a dummy variable of integration. The overall value of the structural acceleration a (or displacement x and velocity v) is also calculated using Eq. (1) by interchanging p with a (or x and v). The value of the exponential time weighting τ should be small enough to capture the amplitudes of cracks with high accuracy. The overall sound pressure level for a given τ value as a function of time t is finally calculated as follows:

$$L_{p,\tau}(t) = 10 \log \left[p_\tau^2(t) / p_0^2 \right] \quad (2)$$

where $p_0 = 20 \mu\text{Pa}$ is the value of the reference sound pressure. The Fourier Transform (FT) of the time domain $p(t)$ signal is conducted as follows [17]:

$$P(f) = \text{FT}[p(t)] = \int_{-\infty}^{\infty} e^{-j2\pi ft} p(t) dt \quad (3)$$

where f represents the frequency and $j = \sqrt{-1}$. It is noted that appropriate overall and FT signal processing parameters including the value of τ and frequency resolution Δf need to be determined. There is also a need to present the general and crack noise characteristics of typical household refrigerators.

Overall, the main objectives of this study are as follows: (i) Design a controlled

experimental test rig to study the crack noises in typical household refrigerators; (ii) determine the appropriate signal processing parameters for overall and Fourier analyses to identify the burst type noises in refrigerators; (iii) present the general and crack noise characteristics of typical household refrigerators under various conditions; (iv) identify the crack noises in household refrigerators by conducting a large number of structural acceleration and sound pressure measurements using the special test rig; (v) explore the root causes of the crack noises in refrigerators; and (vi) summarize some solutions to minimize the crack noises in household refrigerators.

3. Signal processing parameters and noise characteristics of household refrigerators

Typical no-frost household refrigerators are first studied to show their noise characteristics including the crack noises and also to identify signal processing parameters for the overall and Fourier analyses in this section. The properties of the refrigerators studied here are listed in Table 1. A quiet acoustic space is created by placing some panels whose inner surfaces are covered by sound absorbing materials (wedge foams) around the test refrigerator. The background noise measured inside this special room is about $L_p = 20$ dBA. A microphone is placed at the back of the refrigerator to measure the sound pressure propagating from the refrigerator; the distances of the microphone from the refrigerator and the ground being 30 and 70 cm, respectively. The sound pressure level measurements are conducted after the test refrigerator reaches to the steady state conditions (i.e., after it works for about $t = 24$ hours).

Table 1

Properties of the household refrigerators under investigation.

Dimensions	Main Functions
Height (mm) : 1900	Cooling system: No-frost
Width (mm) : 700	Super cooling function: Yes
Depth (mm) : 750	Super freezing function: Yes
Volume	Performance
Total (lt) : 475	Energy efficiency class: A+
Cooler (lt) : 360	Season class: T
Freezer (lt) : 115	Freezing capacity (kg/24 hour) : 6.0

The appropriate values of signal processing parameters are determined here. The preliminary analyses results show that the contribution of the frequencies beyond 6 kHz can be ignored. Therefore, the frequency span is selected as $f = 1$ Hz to 6.4 kHz in the analyses. The value of the time weighting τ is determined by comparing the results of the overall analyses conducted with different τ values; the sample results are presented in Fig. 3. The results show that even the very low-valued noises can be detected when $\tau = 1/32$ s while the crack noises can not be detected correctly when $\tau > 1/4$ s. For example, the amplitudes of the crack noise at about $t = 400$ s in Fig. 3 are about $L_p = 27, 31, 33$ and 34 dBA when $\tau = 1/2, 1/4, 1/8$ and $1/16$ s, respectively. Overall, the analyses are conducted with $\tau = 1/8$ s in this study.

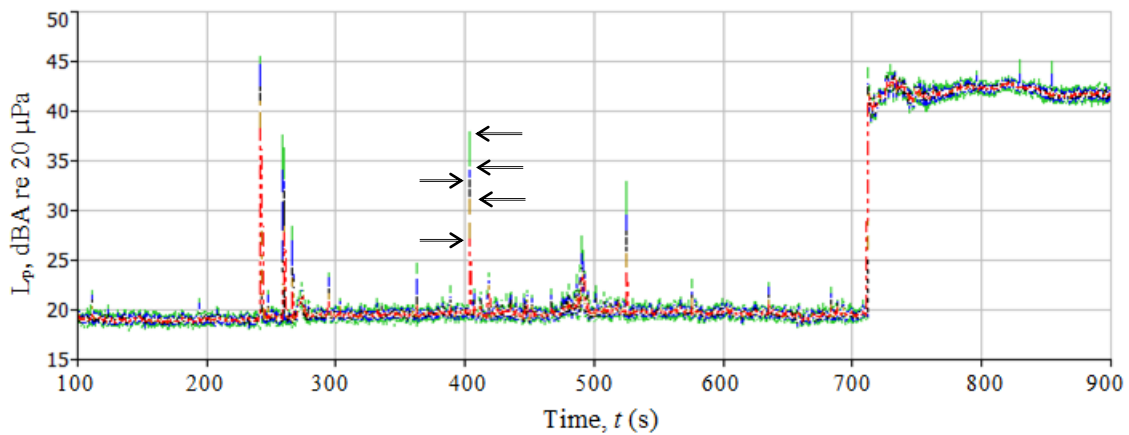


Fig. 3. Effect of time weighting τ on overall sound pressure levels measured at the back of the refrigerator.

Key: — $\tau = 1/32$, — $\tau = 1/16$, $\tau = 1/8$, - - - $\tau = 1/4$ and - . - $\tau = 1/2$ s.

The noise characteristics including the crack noises of the refrigerators under various conditions are presented here. The refrigerators are first loaded using three bricks (the total mass being about $m = 5$ kg) and the temperatures are set $T = -22$ °C with the freezer and $T = +4$ °C with the cooler; the overall sound pressure levels L_p for a duration of $t = 8$ hours are plotted in Fig. 4. It is seen that the number of cracks and also their magnitudes are quite low. Next, the refrigerator is loaded with some hot water (total mass being again about $m = 5$ kg)

and the overall sound pressure levels L_p for this case for a duration of $t = 8$ hours are plotted in Fig. 5. It is seen that the number and magnitudes of the crack noises are higher this time; the denser loading more the crack noises. The crack noises are quite dense especially when $t = 6 - 7$ h. In order to verify these results further, the same sound pressure level measurements are conducted using another similar refrigerator and the temperature at a point close to the heater is also measured this time; the results are plotted in Fig. 6. It is seen that the L_p results in Figs. 5 and 6 are similar and the crack noises for the later case are quite dense when $t = 0.5 - 1.5$ h this time. It is obvious that the defrost occurs when $t = 6 - 7$ h for the measurement given in Fig. 5 and $t = 0.5 - 1.5$ h for the measurement given in Fig. 6 where the crack noises are quite dense and there are rapid changes in the temperature values measured at the heater panel. Although not presented here for brevity, the temperatures are set as super freeze and cooling and the results show that the crack noises increase further for these cases.

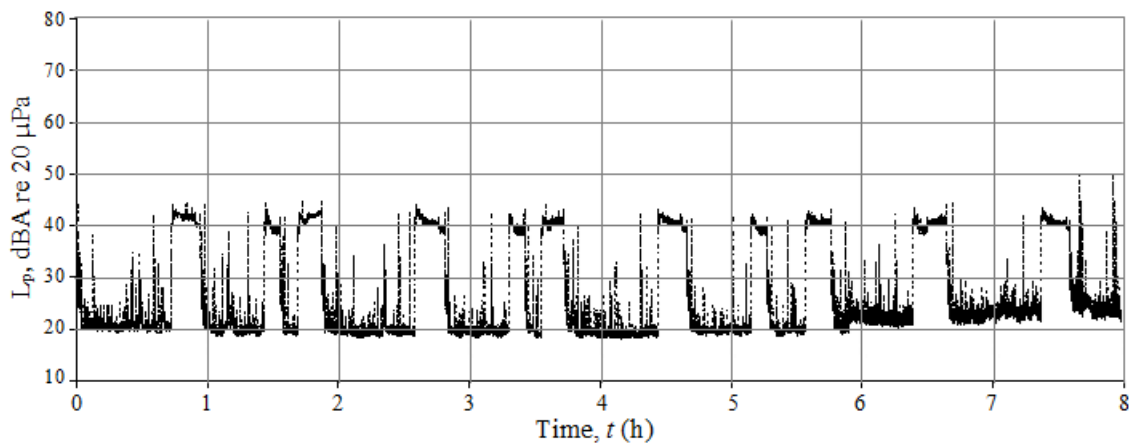


Fig. 4. Overall sound pressure levels measured at the back of the refrigerator for $T = -22$ with the freezer and $T = +4$ °C with the cooler.

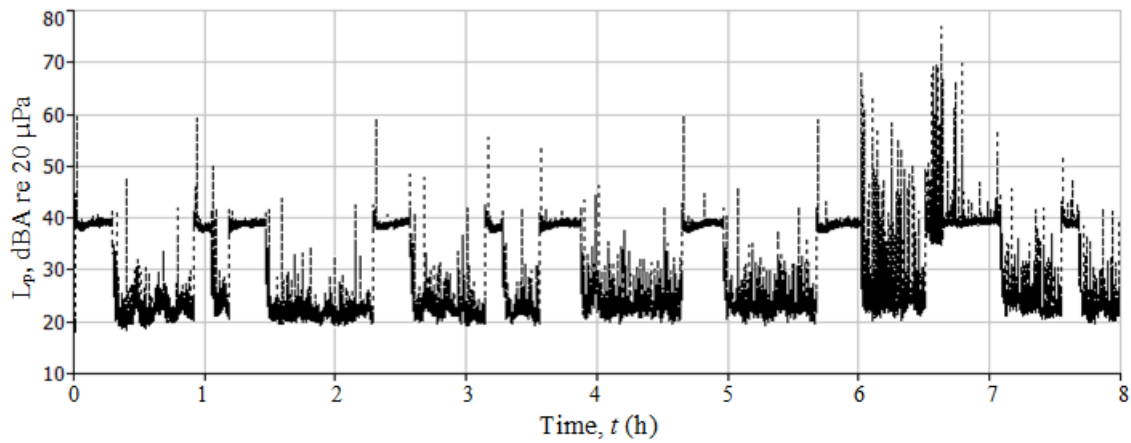
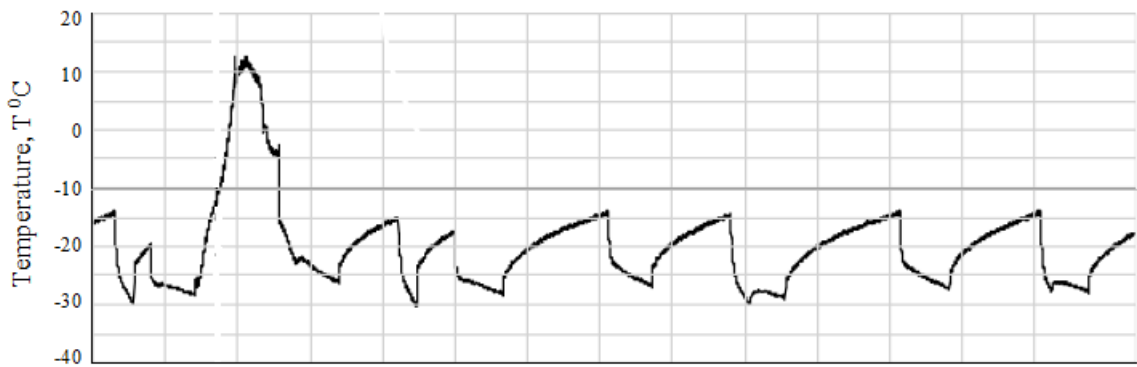


Fig. 5. Overall sound pressure levels measured at the back of the refrigerator for $T = -22$ with the freezer and $T = +4$ °C with the cooler (the refrigerator is loaded with hot water).

a)



b)

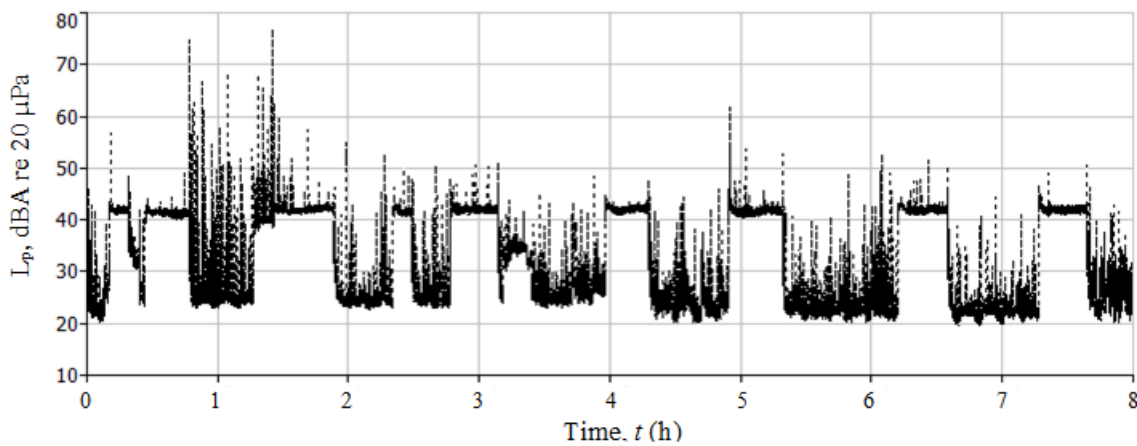


Fig. 6. The temperature measured at the heater panel (a) and overall sound pressure levels measured at the back of the refrigerator (b) for $T = -22$ with the freezer and $T = +4$ °C with the cooler.

It should be noted that the measured cracks are not ideal dirac delta functions [17]; instead they are like triangle pulses and can be expressed as:

$$\Lambda\left(\frac{t}{W}\right) \equiv \begin{cases} 1 - |t|/W & |t| \leq W \\ 0 & \text{elsewhere} \end{cases} \quad (4)$$

where $2W$ is the width of the triangle pulse. The FT of the triangle pulse in Eq. (4) is determined as follows:

$$\text{FT}[\Lambda(W, t)] = W \text{sinc}^2(Wf) \quad (5)$$

where the function ‘sinc’ for the variable ‘ x ’ here is given as $\text{sinc}(x) = \sin(\pi x)/(\pi x)$. The FTs of a few pulses with different widths (W values) are plotted in Fig. 7. A crack should contain energy for a wide frequency range depending on the W value; note that the response of the triangle pulse with $W = 0.05$ ms is nearly flat for the frequency range of interest in this study (i.e., for $f = 0 - 6.4$ kHz). It should be remembered that as the sampling frequency is quite high (i.e., $f_s = 32$ kHz) and thus as the sampling interval is quite low (i.e., $\Delta t = 0.03$ ms), the frequency contents of the cracks can be correctly identified.

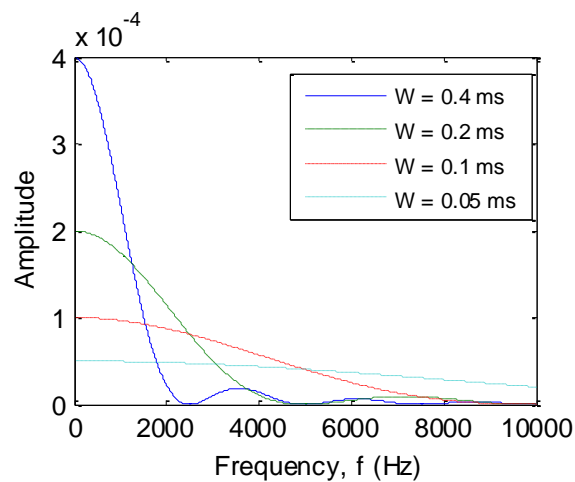
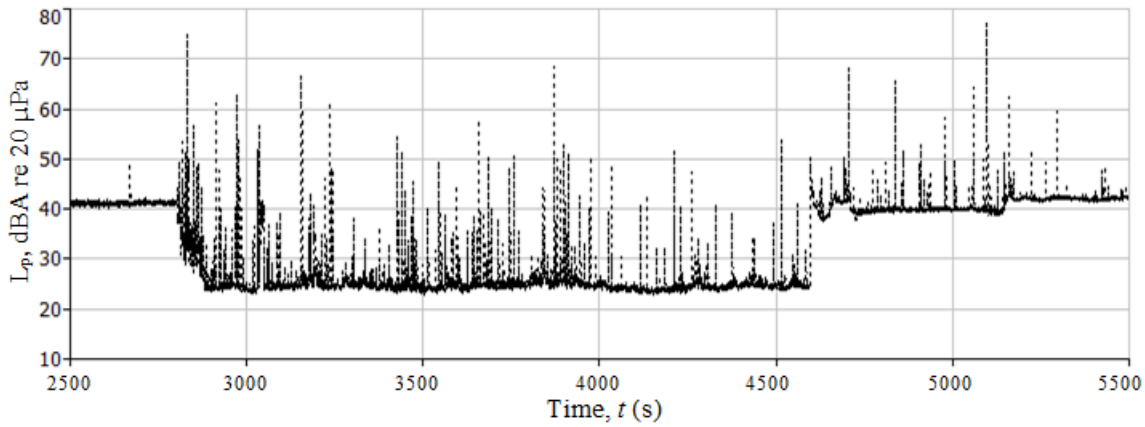


Fig. 7. The FTs of a few triangle pulses with different widths (W values).

The FTs of the sound pressure data including the region where the crack noises are quite dense (i.e., when $t = 2500 - 5500$ s) in Fig. 6 are first conducted using different Δf frequency resolution, averaging time and trigger interval values here to select the appropriate FT signal processing parameters. The results of the overall analyses of the associated data are reproduced in Fig. 8a. In conclusion, the FT signal processing parameters are determined to be as $\Delta f = 4$ Hz and averaging time $t = 0.5$ s (the overlap is %66.7 and the number of averages is 6). The FT of the data in Fig. 8a using the identified signal processing parameters is plotted in Fig. 8b. It is seen that the crack noises contain energy at all frequencies in the frequency range of interest (i.e., for $f = 0 - 6.4$ kHz) though the magnitudes of the crack noises slightly decrease as frequency increases as similar to the theoretical results presented above. It should be noted that the frequency characteristics of the crack noises in refrigerators are further analyzed and examined in detail in Sections 4.3 and 4.4.

Overall, it has been shown that some crack noises are propagated from the typical household refrigerators; however, the components propagating these burst type noises and the reasons behind the mechanisms of these noises are not known. As the sources of the cracks can be any part of a refrigerator, there is a need to utilize a controlled experimental study to explore the root causes of the crack noises as it is carried out in the next section.

a)



b)

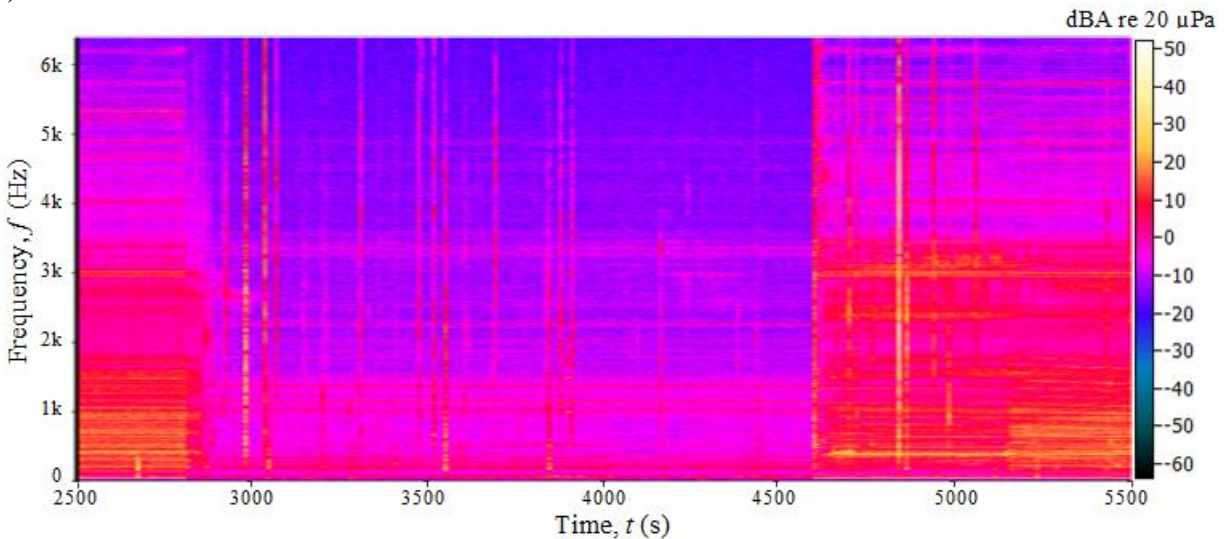


Fig. 8. The overall sound pressure levels (a) and the FT results (b) of the data measured at the back of the refrigerator for $T = -22$ with the freezer and $T = +4$ °C with the cooler.

4. Identification of the crack noises in household refrigerators using the test rig

Here, a systematic study based on the experimental test rig and signal processing parameters presented in Sections 2 and 3 is conducted. The effect of each subcomponent including the heater and the effect of loading on the crack noises in household refrigerators are investigated by conducting various experiments. First, the repeatability of the test rig is checked. After that, the compressor and fan are operated together and separately and the contribution of these two components on the crack noises is investigated. Then, the test rig is loaded with hot water and the

effect of loading on the crack noises is investigated. Finally, the heater is operated and the effect of heating on the crack noises in refrigerators is investigated. The main findings are discussed at the end of this section.

4.1 Experiment scenario 1: Assessment of the test rig

The repeatability of the test rig should be checked and ensured first. The scenario of the experiment for this purpose is presented in Table 2 where the compressor and fan are first on for a while and they are then off; this repeats three times. The temperature, overall structural acceleration and sound pressure levels for this scenario are plotted in Fig. 9. It is seen that the temperature varies between -33 and -20 °C. As seen both in sound and vibration measurements, the test rig including the measurements system and acoustic room is quite repeatable. Results show that there are only a few crack noises whose amplitudes are less than 45 dBA for this measurement.

Table 2
Scenario of the experiment 1 for checking the repeatability of the test rig.

<i>T</i> (s)	Compressor	Fan	Heater
0 - 240	On	On	Off
240 - 1560	Off	Off	Off
1560 - 2160	On	On	Off
2160 - 2760	Off	Off	Off
2760 - 3360	On	On	Off
3360 - 3960	Off	Off	Off

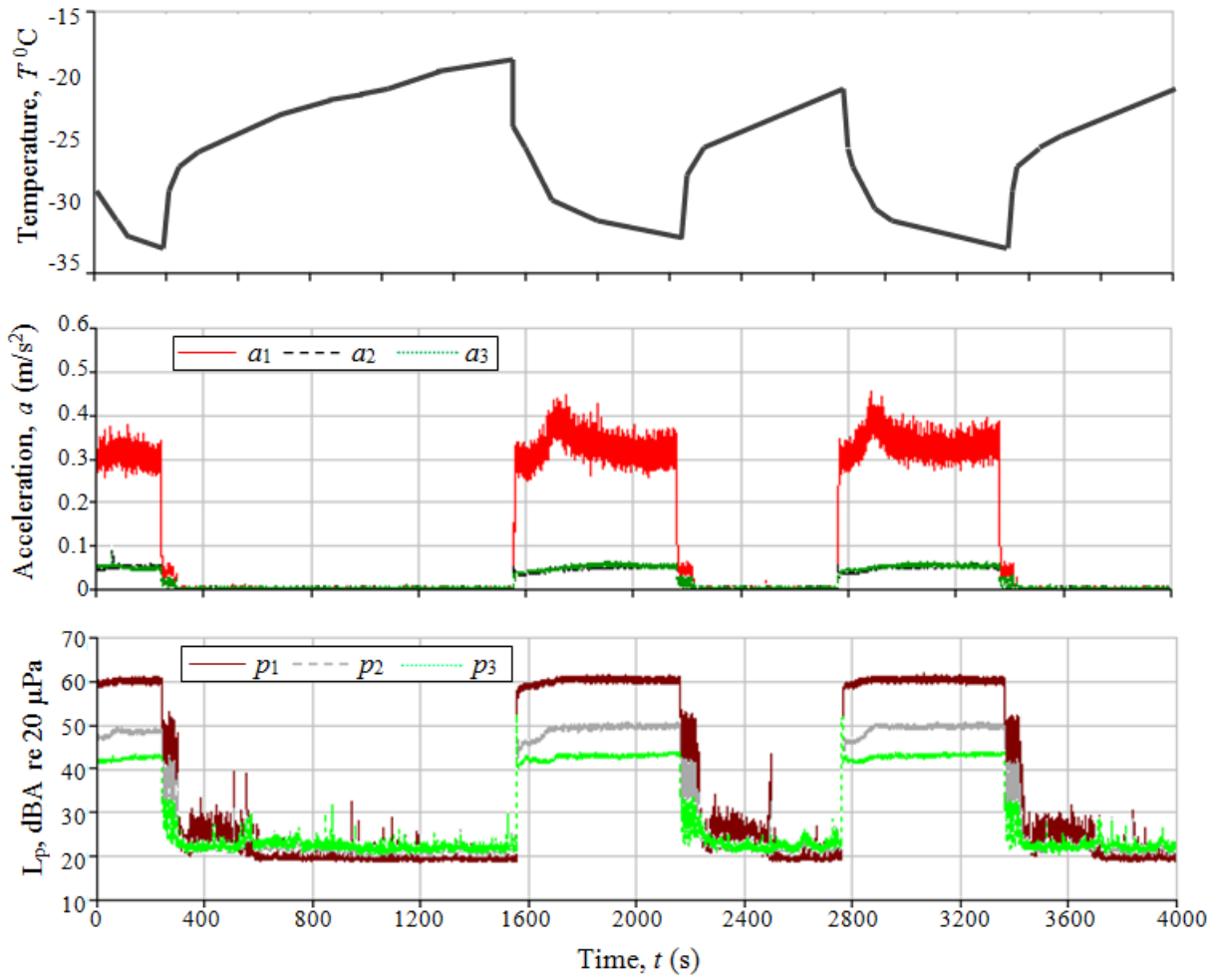


Fig. 9. The temperature, overall structural acceleration and sound pressure levels for the experiment scenario 1 (see Fig. 2 for the sensor positions and Table 2 for the experiment scenario).

4.2 Experiment scenario 2: Effects of the compressor and fan

Here, the compressor and fan are operated together and separately and the contribution of these two components on the crack noises is investigated. The scenario of the experiment for this purpose is presented in Table 3 where both the compressor and fan are on for $t = 0-300$ s (or for the first $t = 5$ minutes), only the compressor is on for the next $t = 600$ s (or $t = 10$ minutes) and all components are off for the next $t = 600$ s. The temperature, overall structural acceleration and sound pressure levels for this scenario are plotted in Fig. 10. It is seen that the background sound pressure level is about $L_p = 20$ dBA; note that the measured sound pressure levels are equal and greater than $L_p = 40$ dBA even when only the compressor is on. This means the special room is quiet and reliable for

these measurements. The contribution of the fan on the total sound pressure level is 2-3 dBA when the evaporator microphone (p_2) is considered. Note that the fan noise is more dominant inside the cabinet as expected. The temperature measured on the heater varies between $T = -22$ and -8 °C. Overall, it is seen that serious crack noises do not occur in this experiment; the amplitudes of the crack noises available are less than 32 dBA.

Table 3

Scenario of the experiment 2 for investigating the effects of the compressor and fan.

T (s)	Compressor	Fan	Heater
0 - 300	On	On	Off
300 - 900	On	Off	Off
900 - 1500	Off	Off	Off

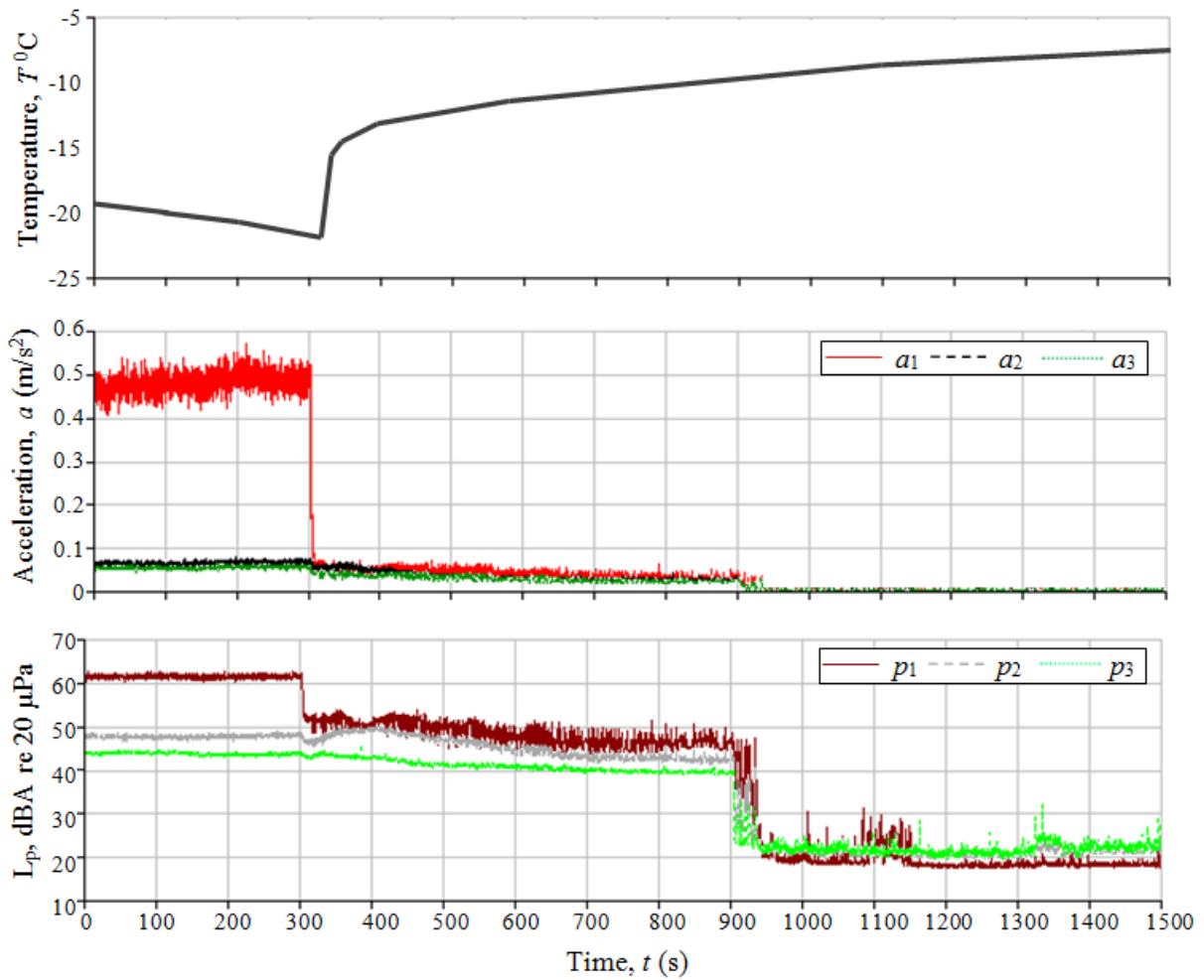


Fig. 10. The temperature, overall structural acceleration and sound pressure levels for the experiment scenario 2 (see Fig. 2 for the sensor positions and Table 3 for the experiment scenario).

4.3 Experiment scenario 3: Effect of the loading

The test rig is loaded with hot water and the effect of the loading on the crack noises is investigated in this section. The scenario of the experiment for this purpose is presented in Table 4 where the test rig is loaded with hot water and the measurements are conducted after loading. The temperature, overall structural acceleration and sound pressure levels for this scenario are plotted in Fig. 11. It is seen that the temperature varies between -27 and -11 °C. There are a few considerable crack noises; the amplitude of one of them measured with microphone 1 (p_1) is about $L_{p1} = 70$ dBA. It is seen that the cracks are also detected by the accelerometers this time. The results show that the measured vibration levels for those cracks are highest at the heater panel (a_1) and they are lowest at the outside panel (a_3). For example, the amplitudes of the crack are $a_1 = 0.48$ m/s² at the heater panel, $a_2 = 0.20$ m/s² at the inside panel and $a_3 = 0.18$ m/s² at the outside panel for the crack with the highest amplitude measured at about $t = 449.5$ s.

Table 4

Scenario of the experiment 3 for investigating the effect of the loading.

T (s)	Compressor	Fan	Heater	Loading
0 - 300	On	On	Off	+
300 - 900	Off	Off	Off	
900 - 1500	On	On	Off	
1500 - 1800	Off	Off	Off	

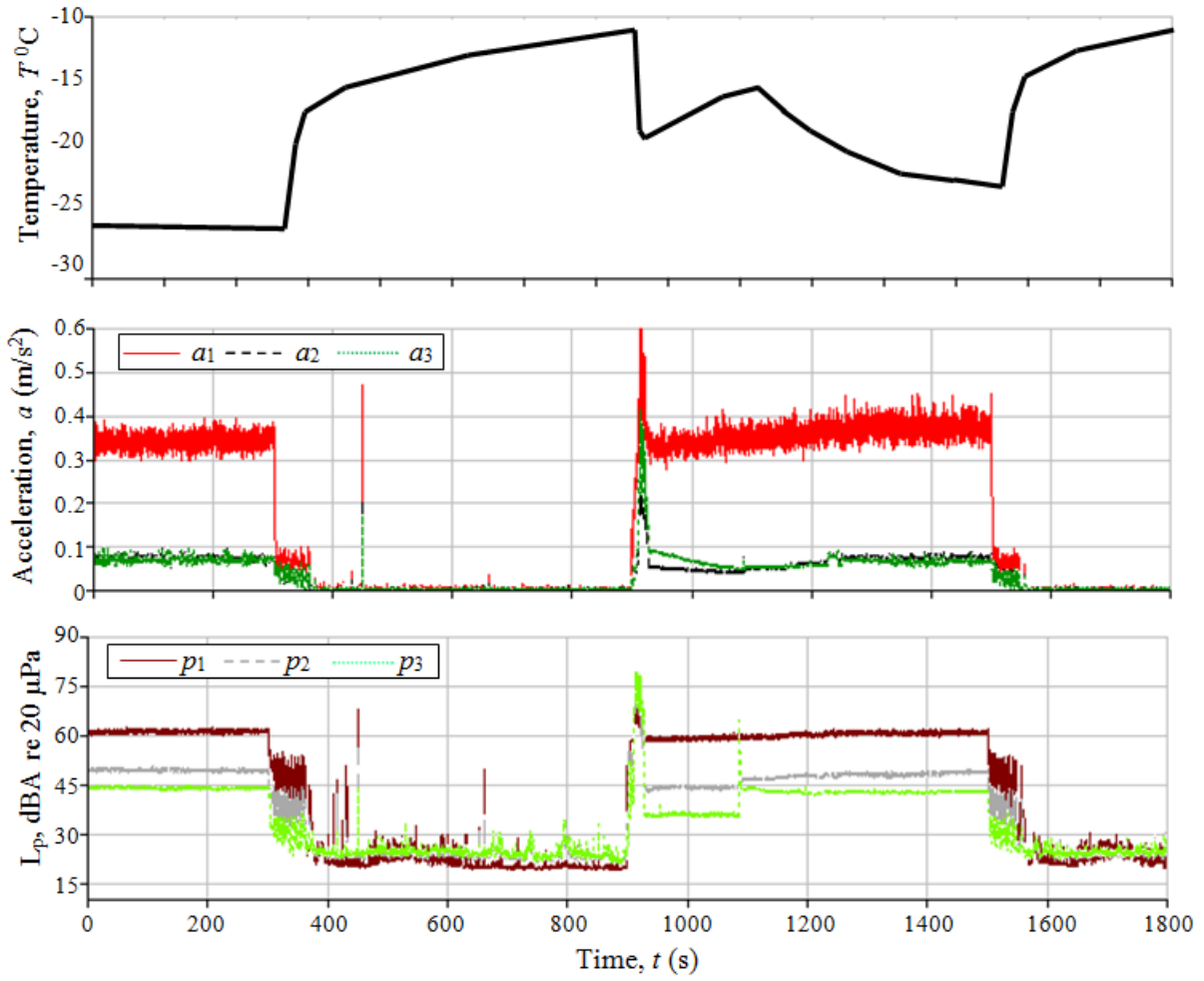


Fig. 11. The temperature, overall structural acceleration and sound pressure levels for the experiment scenario 3 (see Fig. 2 for the sensor positions and Table 4 for the experiment scenario).

The structural acceleration and sound pressure levels for the region containing the crack occurred at about $t = 449.5$ s is re-plotted in Fig. 12. It is seen that the sound pressure levels are about $L_{p1} = 70$ dBA, $L_{p2} = 55$ dBA and $L_{p3} = 45$ dBA. The FTs of the acoustic and structural acceleration data between $t = 448$ and 452 s are also conducted and the results are presented in Fig. 13. It is seen that the structural accelerations are quite high on the heater panel (a_1) and their magnitudes are dominant even up to $f = 12$ kHz for a_1 although the amplitudes decrease from $f = 8$ kHz to 12 kHz. Similarly, the L_{p1} magnitudes are quite high for a wide frequency range.

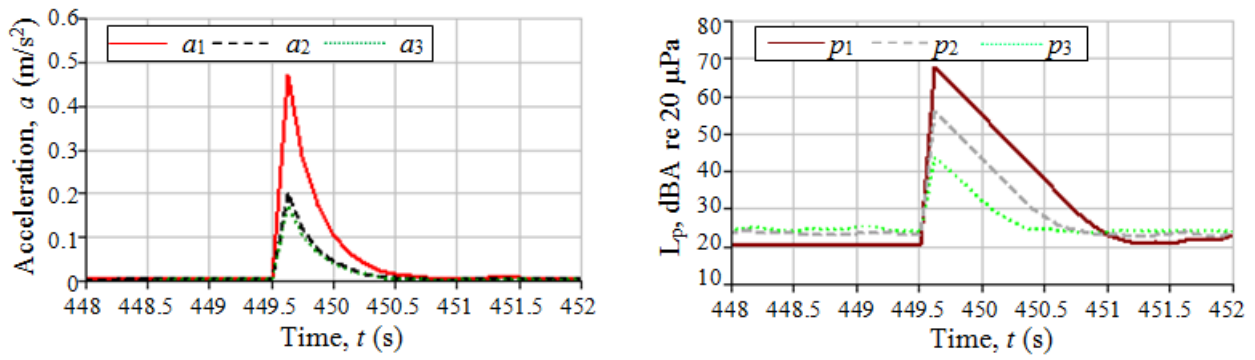


Fig. 12. The overall structural acceleration (left) and sound pressure levels (right) for the experiment scenario 3 (see Fig. 2 for the sensor positions and Fig. 11 for all overall data).

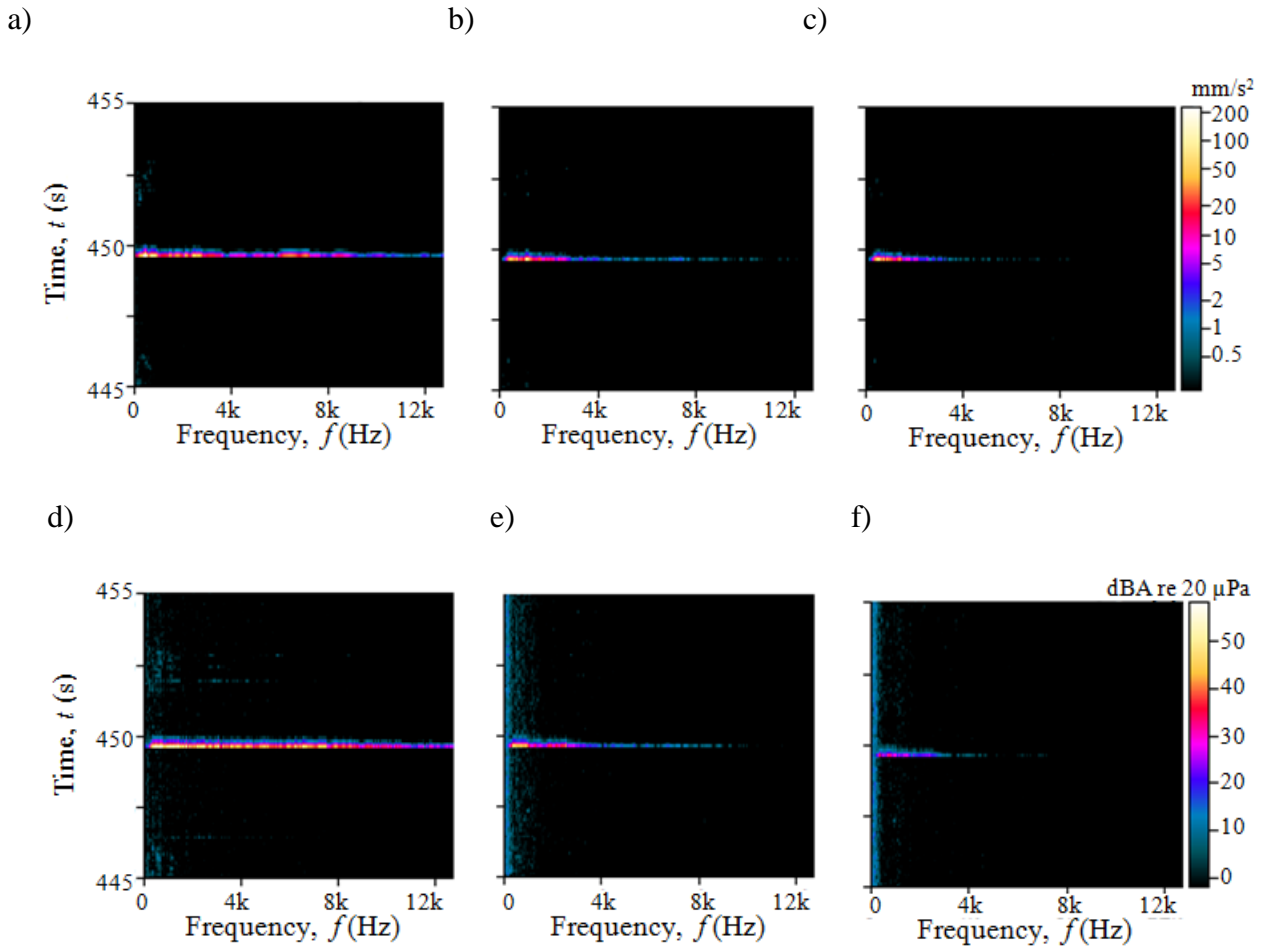


Fig. 13. The FTs of the structural acceleration a_1 (a), a_2 (b) and a_3 (c) and the sound pressure p_1 (d), p_2 (e) and p_3 (f) for the experiment scenario 3 and the data between $t = 448 - 452$ s (see Fig. 2 for the sensor positions and Fig. 11 for all overall data).

4.4 Experiment scenario 4: Effect of the heating

In this section, the heater is operated and the effect of the heating on the crack noises in refrigerators is investigated. The scenario of the experiment for this purpose is presented in Table 5 where the test rig is loaded with hot water and the measurements are conducted after the loading while the heater is also operated this time. The temperature, overall structural acceleration and sound pressure levels for this scenario are plotted in Fig. 14. It is seen that the temperature varies between -22 and 20 °C as the heater is operated this time. The FTs of the structural acceleration a_1 and the sound pressure p_1 are also plotted in Fig. 15. It is seen that there are a large number of cracks during the heating period, especially during the early phase of the heating process. The amplitude of the crack measured (at about $t = 1330$ s) with the microphone inside the cabinet (p_1) is greater than 80 dBA and the amplitude of this crack measured by the accelerometer on the heater panel is greater than 1.2 m/s² this time. Many cracks including the crack detected at about $t = 1330$ s have energy contributions at a wide frequency range (i.e., for $f = 0 - 6.4$ kHz).

Table 5
Scenario of the experiment 4 for investigating the effect of the heating.

T (s)	Compressor	Fan	Heater	Loading
0 - 1200	On	On	Off	+
1200 - 1320	Off	Off	Off	
1320 - 1920	Off	Off	On	
1920 - 2400	On	On	Off	

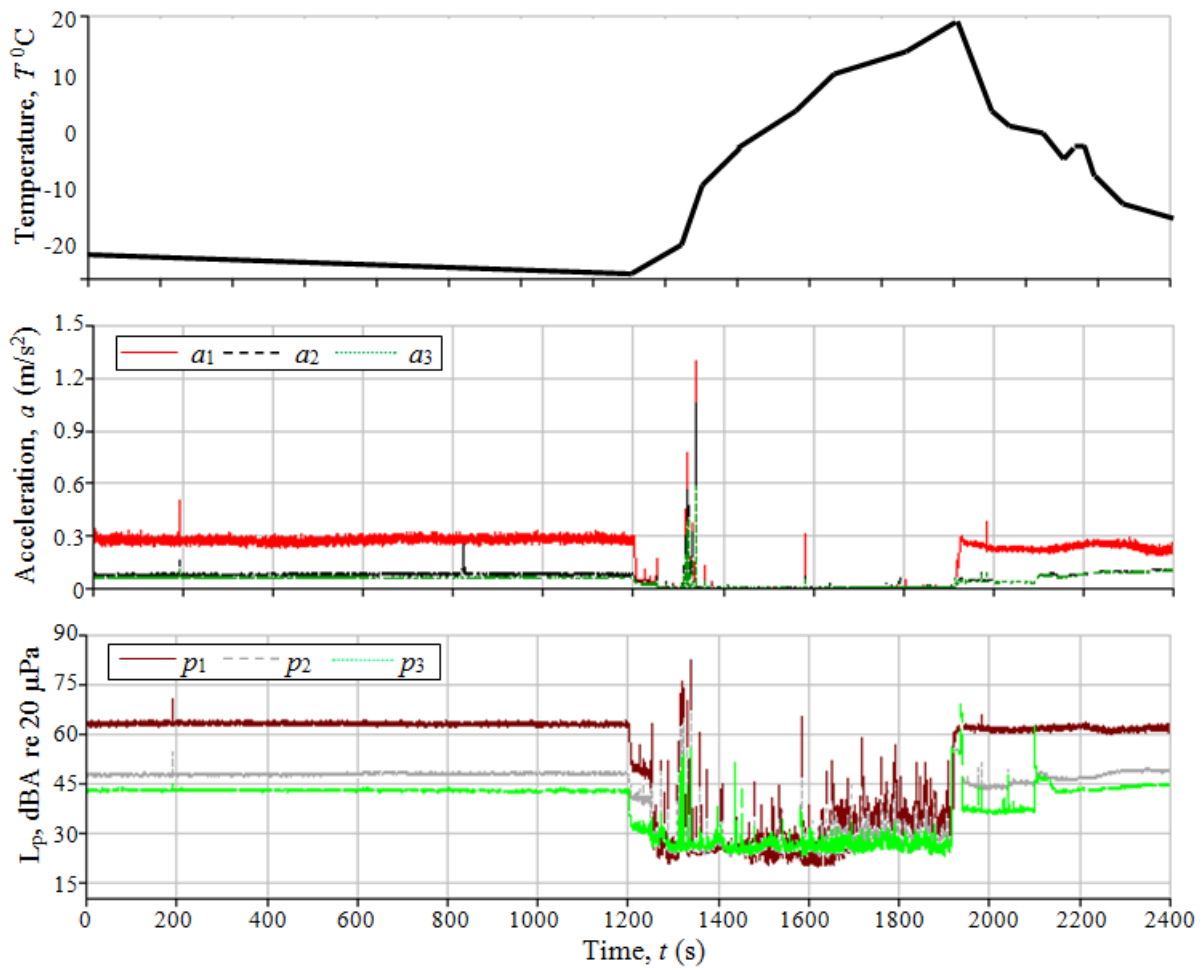
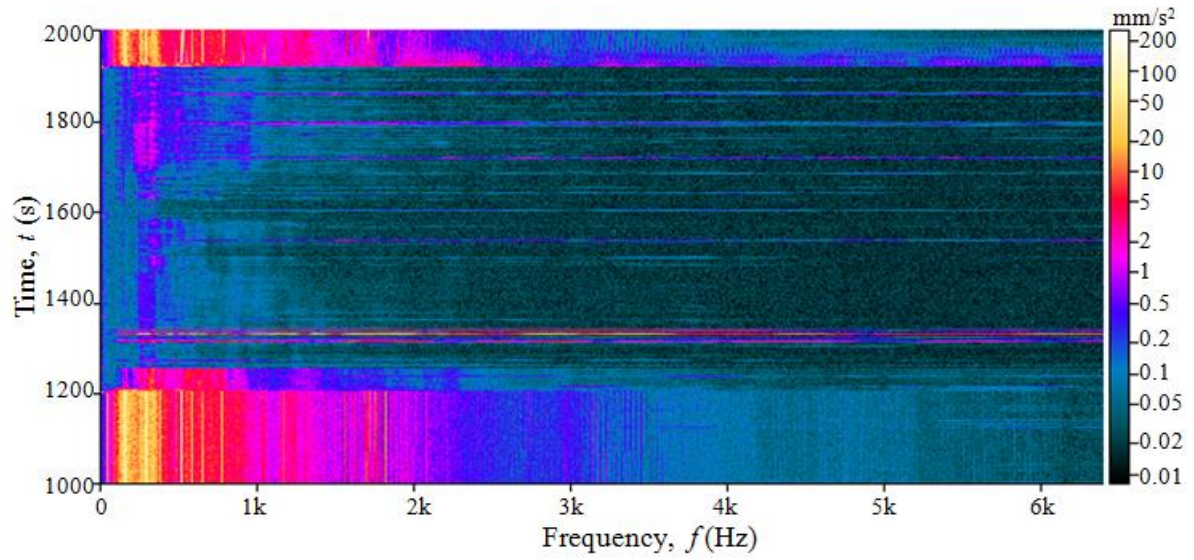


Fig. 14. The temperature, overall structural acceleration and sound pressure levels for the experiment scenario 4 (see Fig. 2 for the sensor positions and Table 5 for the experiment scenario).

a)



b)

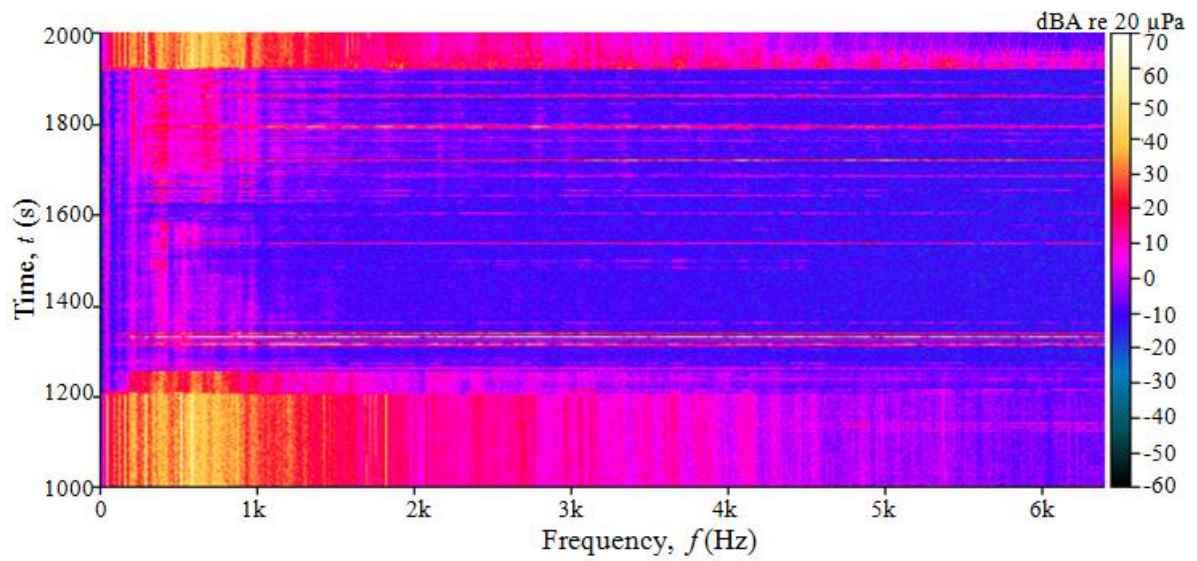


Fig. 15. The FTs of the structural acceleration a_1 (a) and sound pressure p_1 (b) for the experiment scenario 4 (see Fig. 2 for the sensor positions and Fig. 14 for all overall data).

4.5 Discussion

The results presented above show that the number and amplitudes of the cracks measured with accelerometers and microphones increase when the refrigerator is loaded and the heater is operated. The results of the overall and FT analyses indicate that the cracks occur due to the rapid temperature changes and the main source of the crack noises is the heater panel as the measured vibration levels of the cracks being highest at the heater panel. Note that the heater causes the temperature of the heater panel to increase very rapidly at the beginning of the defrost process and its temperature decreases when also the defrost process is completed and the refrigerator starts to cool itself by operating the compressor and/or fan. Due to the rapid temperature changes, contraction and expansion create thermal stresses in the materials and eventually these burst type sounds occur.

There are a few ways to minimize the crack noises in household refrigerators. Local heating can be considered to avoid the rapid heating process thus the thermal stress concentrations in the structural components such as heater panel. Similarly, the heating rate can be decreased to avoid the rapid heating process. The heater can also be detached from the heater panel if possible. Furthermore, the heater (plastic) panel can be redesigned so that it can include some ribs and stiffeners (instead of being flat) to minimize the acoustic radiation. In addition, passive damping treatment can also be applied on the panel to reduce the crack sound emitted from the panel. All these solutions need to be considered by also taking account the thermal efficiency of a refrigerator and this process requires an optimization procedure, which can be the subject of a future work.

5. Conclusion

This paper investigates the identification of the crack noises in household refrigerators and explores their root causes. The appropriate signal processing parameters for the overall and Fourier analyses to study the crack noises in household refrigerators are first determined and sound

pressures measured at the back of typical household refrigerators under various conditions are presented. Then, a special test rig providing remote control of the subcomponents is designed and it is used to conduct structural acceleration and sound pressure measurements to identify the crack noises. To the best of the Authors' knowledge, this is the first paper in the literature identifying the crack noises in household refrigerators and exploring the reasons behind the mechanisms of such noises.

Results show that the crack noises occur due to the rapid temperature changes in structural components. The contraction and expansion due to rapid temperature changes create thermal stresses in the materials and eventually these burst type sounds occur. The heater panel which is very close to the heater and the most affected component from the heating is the main source of the cracks. The appropriate design of the heater panel and optimization of the heating process, which will aim to decrease the rapid temperature changes and thus the contraction and expansion of structural components, can minimize the very annoying crack noises in the modern household refrigerators. It is also apparent that there is a need for subjective recognition of crack noises. It should be noted that the subjective recognition of the crack noises in household refrigerators is considered as a future investigation.

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