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A STUDY ON SOUND LEVEL DIFFERENCES IN WORKING MODES OF A REFRIGERATOR WITH AN INVERTER COMPRESSOR

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ABSTRACT

Efforts in noise reduction of household refrigerators have led to ultra-low sound level claims on energy labels (some of them below 30 dBA sound power level, as of 2024). Further incentives to keep bringing these claims down comes from legislation of energy labels creating, so called "acoustic noise emission classes" (from A to D for most household appliances). Modern refrigerators come equipped mostly with inverter compressors (that can change rotational speed based on cooling demand), also in an attempt to meet stringent energy consumption requirements. These compressors, however, have quite a broad rotational speed range (usually beyond 3000 rpm). There is a risk that, at the two extremes of speed range (minimum and maximum speed) it may lead to substantially different perception of the same appliance by end-users. This study aims to provide some real product testing results of a difference between the working modes of several modern refrigerators, where in some cases the difference can be up to 10 dBA (!). It also provides some discussion on what a legislation body can do with this information to support more integral sound performance from the same product and promote design of quiet appliances not only in specific working conditions.

Keywords: *refrigerator noise, inverter compressor, sound quality, psychoacoustics*

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1. INTRODUCTION

Officially declared sound power levels of modern refrigerators are ever decreasing. In European markets, the mandatory declaration of acoustic noise emissions is subject to standardization. The latest issue of regulation related to energy labeling [1] has proposed a 4 step scale in which sound power levels are clustered (see Table 1).

Table 1. Airborne acoustical noise emission classes.

Airborne acoustical noise emission [re 1 pW]	Airborne acoustical noise emission class
<30 dB(A)	A
≥ 30 dB(A) and <36 dB(A)	B
≥ 36 dB(A) and <42 dB(A)	C
≥ 42 dB(A)	D

The highest class of noise emission, for refrigerators, calls for values below 30 dBA sound power level. Many educational materials compare that level (although, obviously expressed in sound pressure level) to a soft whisper. Former publication of the authors suggest that this level might be below what typical customers can hear in their home environment [2]. In the light of manufacturers' competition (to find a design that meets demand of the highest class of noise emission), natural law of diminishing returns, it is worth looking more holistically at the sound produced by these household appliances. Since some time already, most of the modern refrigerators come equipped with an inverter compressor.

The goal of this study was to measure the difference in terms of sound power level and psychoacoustics parameters at the two extremes of compressor speeds range. Another goal was to try to correlate that to the comments expressed by final customers in their “5 Stars” rating. Finally, authors of this paper would like to recommend if and how the collected information could lead to testing standard, and/or energy labeling regulation modification.

2. SUBJECT OF STUDY

Authors had analyzed various different appliances having inverter compressors, from the most common commercial segment in Europe, like free-standing or built-in bottom mounted refrigerators (i.e. freezer compartment is mounted at the bottom). One can tell which refrigerators are equipped with an inverter compressor, by a marketing claim such as “Active Inverter Compressor” [3], “Digital Inverter Technology” [4] or “Intelligent Inverter Technology” [5].
A typical inverter compressor has a rather broad speed operating range exceeding 3000 rpm. It spans from around 1200 to 4500 rpm. Most of the producers (both compressor and refrigerator) base their benefit claims (i.e. energy consumption, noise, etc.) on the performance of the product at lower end of the compressor speeds (for example “Low noise and vibration - More comfort for users” [6]). It is interesting therefore to understand the performance at the other end of the performance scale (i.e. higher compressor speeds) in terms of measured sound parameters. Especially the difference between both performance ends, in the light of some other publication findings regarding the least noticeable difference in sound [2,7].

3. VOICE OF CUSTOMER ANALYSIS

To assess customer impression of the sounds made by the subject of the study, authors have analyzed “5 Stars” rating, very common in Internet, as a source of Voice of Customer. A 5-star survey is a customer feedback questionnaire that uses a 5-point rating scale to assess satisfaction with a product or service. The concept is simple: customers are asked to rate a product, service, or experience on a scale of 1 to 5 stars [8]. These reviews are spontaneous in nature, and would not describe in detail (as one could expect from a formal sound jury) the feelings of listeners, but it still gives interesting insight into how these products’ sounds are perceived when used at home. For the majority of services, the dominant ratings are close to 5, followed by 4, yielding an average score around 4.5. 1 and 2 star ratings are usually sporadic and related to complete malfunction of a product or service, that doesn’t happen that often. Authors focused on reviews where keywords “noise”, “vibrations” or similar are used. In addition, a priority was given to overall ratings of less than 5 Stars, which reflects some dissatisfaction of the end-user, but avoiding situations where product didn’t work. Unfortunately, in majority of cases, users will just use a few words repeatedly as “sound”, “noise(y)” or “loud” which can be visualized with simple world cloud (Figure 1).

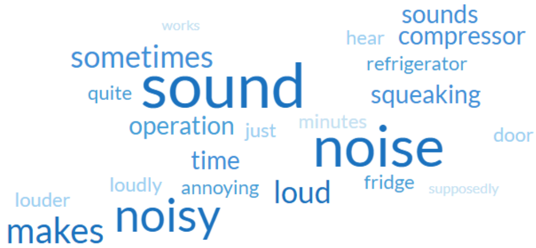

Figure 1. Distribution of user ratings, focusing on reviews mentioning noise-related terms.

In some cases however, end users are more detailed in their feedback and these comments can give an insight into how an inverter compressor refrigerator is perceived at home. Selected examples that could lead to some observations related to compressor working in different modes (speeds):
“*noisy not just when door opens it randomly makes a noise unsure why*”
“*a bit noisy when you have had the door open for a while*”
“*when starting, it may make a rattling noise, probably when starting the compressor, the sound of operation gets louder and lasts for a few minutes, then quietens down to normal operation, but sometimes it goes on like this for 15 minutes.*”
“*High frequency buzzing noise*”
“*At first I was skeptical because the device was a little louder when turning. But wait after one night, he is super quiet*”
“*It is not silent because the value is averaged over a period of time but supposedly this is normal with new gasses and inverter compressors*”
“*(When) compressor begins to cool, then it is quite noisy. Therefore only 3 stars. It's annoying really !! !*”
The relation to user-activated events (like door opening, starting a product) requires some clarification. A refrigerator typically includes a temperature probe that reads real temperature and compares that with a set temperature. Compared to the difference between the two, it sets the following sequence of cooling system operation (large difference requires more effort from compressor, thus higher speed). It is then understandable that after such

customer initiated events (door interaction, first start up) inverter compressor may increase its speed temporarily.

4. MEASUREMENTS & ANALYSIS

4.1 Testing conditions

Testing conditions were based on internationally recognized IEC 60704-2-14 standard [9]. It calls for sound power level measurements under reproducible conditions. These conditions are often referred to as “steady-state”, which leads to an inverter compressor working at minimum speed (for temperature maintenance in the refrigerator). This standard was used to capture measurement data at lower end of compressor speeds.
To capture product’s sound at the other end of the compressor rpm range scale, authors used one of the two options:

- fast cooling or freezing option that is selectable in user interface
- first cycle operation when product was completely warm

Obtained measurements (running cycles) in this way, were not steady in time and temperature. Authors decided to cut a portion of time where the compressor was running at max available speed, as can be seen in Figure 2.

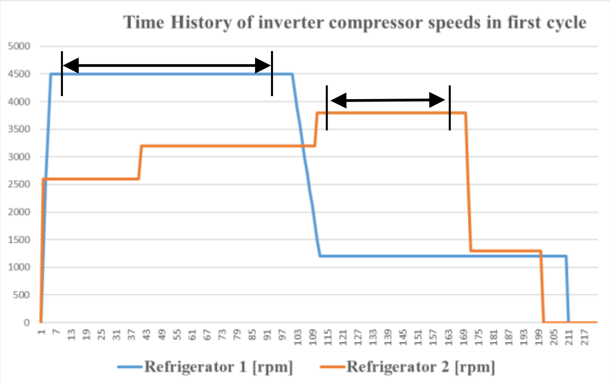

Figure 2. Selected compressor maximum speeds, two example selections.

4.2 Sensors position & software for analysis

Sound power level (IEC) procedure microphone layout was used to record the sound from one of its microphones (the frontal one, which sits more or less 1m from the refrigerator front door and 1,5m above the floor). To have a better understanding of compressor speeds during the cycles, the additional accelerometer was used, mounted on the compressor. Registration of all signals was done in a hemi-anechoic chamber using HBK Pulse Labshop software, while the psychoacoustic analysis was done using Head Acoustics Artemis.

4.3 Sound power level analysis

Figure 3 shows results of testing of 12 refrigerators coming from 6 different manufacturers.

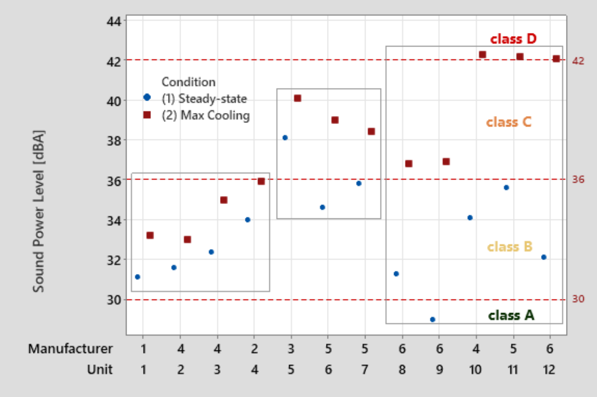

Figure 3. Measured sound power levels of refrigerators working in different modes with airborne acoustical noise emission classes.

The data can be clustered into 3 groups:

- left side box - minimal difference (less than 3 dBA) between the two extreme working modes of compressor
- middle box - medium difference (not more than 5 dBA)
- right side box - large difference (up to 10 dBA)

Additionally, authors added the limits of airborne acoustical noise emission classes (as per [1]). It is visible that the refrigerators models from the left side box represent sound power level emission belonging to the same emission class, despite working in different modes.
Refrigerators from the middle box exhibit different emissions depending on the working mode, but the difference is one emission class only.
The most severe situation is in the right side box, where the difference between working modes can span across two different classes. Perhaps, the most eye-catching is the case of a refrigerator that belongs to A class noise emission, when working in steady-state condition, while C class when working in max cooling mode.

4.4 Psychoacoustic analysis

The acoustic and psychoacoustic characteristics of product sounds operating under both normal and maximum speed conditions were examined in more detail. In this regard, recordings from five different products (under both normal and maximum speed conditions) were analyzed in depth. This chapter presents detailed analyses of these 10 recordings. The duration of the recordings ranges from 1000 seconds to 8000 seconds. Since the operating conditions varied from device to device, the recordings were considered in their entirety without any cuts, with measurement conditions and points identical to section 4.2.
To establish a comparison framework at the beginning, the A-weighted average sound pressure levels of the 10 recordings from the front microphone (as described in Chapter 4.2) are provided in Table 2. The sound levels of devices across different speed conditions show notable differences. For normal speed conditions, device 1 has the highest sound level at 21.5 dB(A), while device 5 has the lowest at 17.2 dB(A). The sound levels for the devices increase substantially under maximum speed conditions. Device 5 shows the greatest spike, with a maximum speed sound level of 30.9 dB(A), compared to the 28.0 dB(A) of device 1, which indicates a considerable variation in level when switching from normal to maximum speed. The device with the least variation in sound level is device 2, with a change from 18.2 dB(A) at normal speed to 20.6 dB(A) at maximum speed (a difference of 2.4 dB). The largest change is observed in device 5, which increases from 17.2 dB(A) at normal speed to 30.9 dB(A) at maximum speed (a difference of 13.7 dB). These differences described above are summarized in Table 3.

Table 2. Averaged A-weighted sound pressure levels of five selected devices for normal compressor speed and maximum compressor speed.

Stimuli	L(A)/dB(SPL)
Dev1-Normal Speed	21.5
Dev2-Normal Speed	18.2
Dev3-Normal Speed	19.2
Dev4-Normal Speed	18.9
Dev5-Normal Speed	17.2
Dev1-Maximum Speed	28.0
Dev2-Maximum Speed	20.6
Dev3-Maximum Speed	23.8
Dev4-Maximum Speed	25.3
Dev5-Maximum Speed	30.9

Table 3. Difference between averaged levels of normal and maximum compressor speed for each device.

Device	Difference in L(A)/dB(SPL)
Dev1	6.5
Dev2	2.4
Dev3	4.6
Dev4	6.4
Dev5	13.7

To better understand the variation in differences between devices under normal and maximum working conditions, subsequent evaluations will be presented based on the differences between device 2 and device 5, which show the smallest and largest differences, respectively. The averaged FFTs for normal and maximum conditions for these two devices are shown in Figure 4 and Figure 5, respectively. As seen in these two Figures, while there is a change in the fundamental operating frequency for device 2, this change does not appear to significantly affect the amplitude. Additionally, the variations observed in the higher frequencies are likely below the audible threshold [2]. However, the case is different for device 5, where a prominent peak at the fundamental operating frequency stands out. Moreover, the increase in the 300–1000 Hz range is clearly visible, and it would not be incorrect to suggest that these values are also within the audible range.
As is the case with all refrigerator noise measurements, these recordings are not entirely free from unexpected artefacts. Intermittent noises and internally varying conditions are expected occurrences. To provide a clearer explanation of these effects, the spectrograms for both conditions of these two devices are presented in Figures 6 and 7.

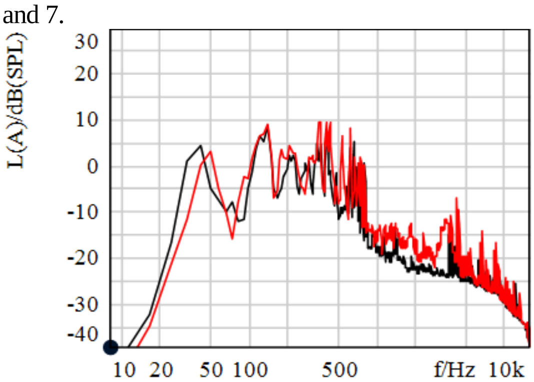

Figure 4. Spectrum of the normal (black) and maximum (red) working condition of device 2 (A-weighted, spectrum size: 4096).

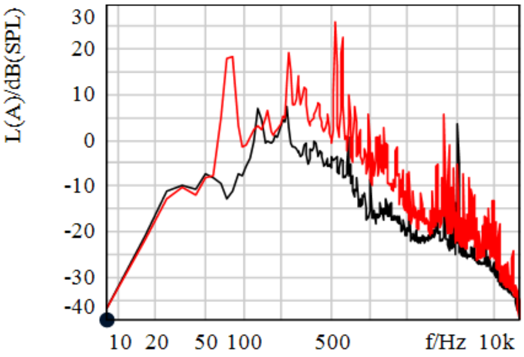

Figure 5. Spectrum of the normal (black) and maximum (red) working condition of device 5 (A-weighted, spectrum size: 4096).

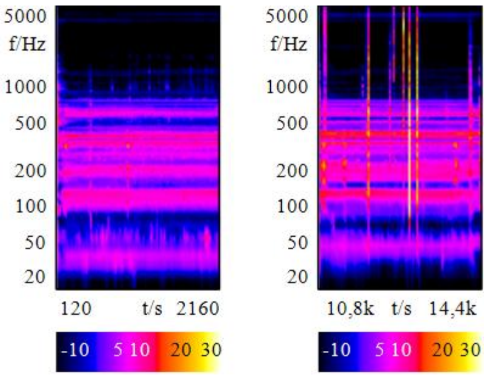

Figure 6. Spectrogram of the normal (left) and maximum (right) working condition of device 2 (A-weighted, spectrum size: 4096).

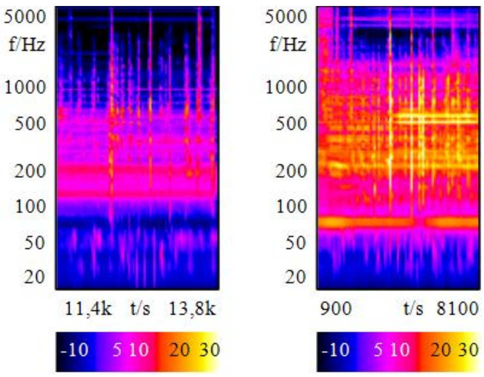

Figure 7. Spectrogram of the normal (left) and maximum (right) working condition of device 5 (A-weighted, spectrum size: 4096).

To further understand the perceptual differences between the devices, average loudness values of 10 recordings were calculated. Table 4 shows the calculated average loudness values based on ISO532. Similar to the A-weighted sound levels, device 5 exhibits the largest increase in loudness from normal to maximum speed, rising from 0.145 soneGF to 1.335 soneGF—an almost nine-fold increase. This indicates that, perceptually, the change in sound for Device 5 is significantly more noticeable compared to the others.
Additionally, for Device 1, although the sound level increased by 6.5 dB from normal to maximum speed, the perceived loudness more than tripled (from 0.296 soneGF to 0.981 soneGF). This indicates that there is not a linear relationship between these two parameters, especially at low absolute values of both quantities, and considering the potential influence of low-frequency tonal content, likely originating from the first-order compressor operation. Moreover, since the level increment required to double the loudness is less than 10 dB at lower levels [10], this difference can be attributed to this effect.

Table 4. Loudness (N5, according to ISO532) levels of normal and maximum compressor speed for each device.

Stimuli	N5/soneGF
Dev1-Normal Speed	0.296
Dev2-Normal Speed	0.173
Dev3-Normal Speed	0.205
Dev4-Normal Speed	0.184
Dev5-Normal Speed	0.145
Dev1-Maximum Speed	0.981
Dev2-Maximum Speed	0.233
Dev3-Maximum Speed	0.342
Dev4-Maximum Speed	0.670
Dev5-Maximum Speed	1.335

To illustrate the temporal changes of loudness, the following figures (Figure 8 and Figure 9) show loudness values over time. It should be noted that the x-axis has been recast; meaning temporal smoothing was applied to enhance the visualization of these changes. For device 2, the differences were minimal, whereas for device 5, abrupt increase in loudness, especially at the late portion of this working cycle can easily be seen.

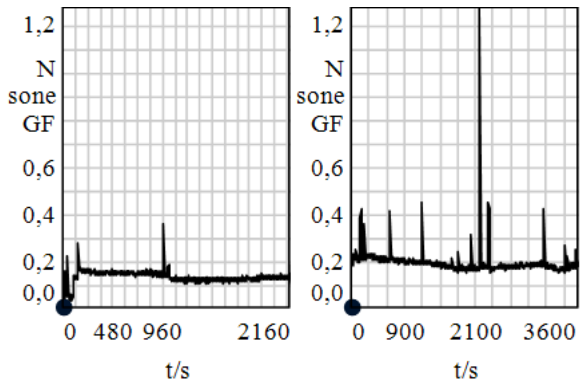

Figure 8. Loudness over time (ISO 532) of the normal (left) and maximum (right) working condition of device 2.

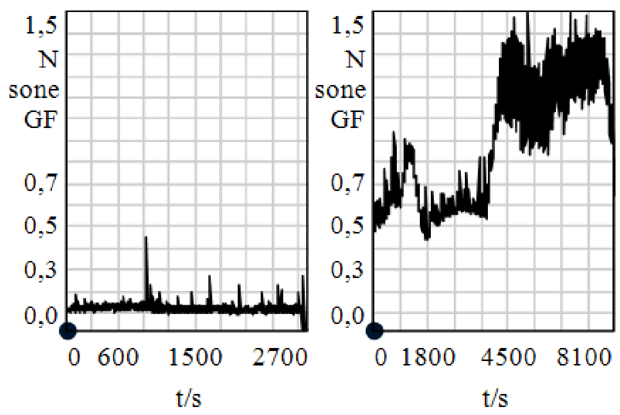

Figure 9. Loudness over time (ISO 532) of the normal (left) and maximum (right) working condition of device 5.

Sharpness is another important parameter for explaining perceptual differences between recordings. Given that loudness levels vary between conditions, comparing both the Aures and Bismarck sharpness models is appropriate. The Aures model accounts for the influence of loudness variations on sharpness, whereas the Bismarck model is primarily used to compare differences between recordings with similar loudness levels. Table 5 presents the sharpness values of the recordings according to both models. The sharpness values do not show a clear trend. Unlike loudness, no distinct separation between conditions is evident. Maximum observed sharpness change between models is approximately 20 percent. For device 4, although the level increased for 6.4 dB for maximum speed, sharpness values tend to decrease. This could be explained by a stronger low frequency participation. For device 5, on the other hand, although the levels increased significantly, Aures sharpness values stayed almost constant. This unclear sharpness trend highlights the presence of varying characteristics in the balance between low and high frequencies.

Table 5. Sharpness (according to Aures and Bismarck model) levels of normal and maximum compressor speed for each device.

	Sharpness [S/acum]	
Stimuli	**Aures**	**Bismarck**
Dev1-Normal	0.414	0.479
Dev2-Normal	0.319	0.336
Dev3-Normal	0.452	0.502
Dev4-Normal	0.589	0.550
Dev5-Normal	0.605	0.449
Dev1-Maximum	0.501	0.498
Dev2-Maximum	0.379	0.408
Dev3-Maximum	0.476	0.569
Dev4-Maximum	0.482	0.470
Dev5-Maximum	0.622	0.530

Lastly, an important factor for refrigerator noise, especially at maximum speed, is tonality. As is well known, changes in motor speed lead to various NVH issues. Within a refrigerator, multiple alternative noise and vibration transmission paths exist, making it challenging to find a single solution that addresses all of them simultaneously. Due to the rotational nature of the compressor, different excitation and transfer path components can result in distinct tonal noises. Even when the overall noise level of the refrigerator remains relatively low, the presence of tonal components can significantly contribute to annoyance. To illustrate this effect, tonality values were calculated for selected refrigerator recordings at both normal and maximum working speeds. Figure 7 shows the spectrogram data for Device 5, while Figure 10 presents the hearing model tonality values for both recordings. It can be observed that, under maximum conditions, a dominant tonality is present. Since the selected example, Device 2, does not exhibit any tonality, we can evaluate another example, Device 4. Figure 11 displays the spectrograms for Device 4 at both normal and maximum operating speeds. The tone-to-noise ratio values calculated for the same device are shown in Figure 12. A clear difference is observed between the two conditions based on the tone-to-noise ratio calculations. Notably, the high penalty values calculated at higher frequencies should be interpreted with consideration for the hearing threshold. It is important to note that these recordings were made in an anechoic environment, and in normal listening conditions, room effects at these frequencies should also be taken into account [2].

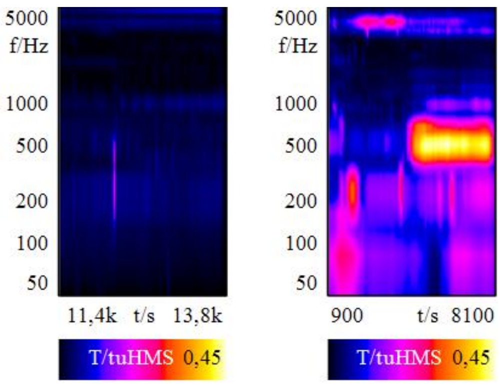

Figure 10. Tonality (Hearing Model) of the normal (left) and maximum (right) working condition of device 5

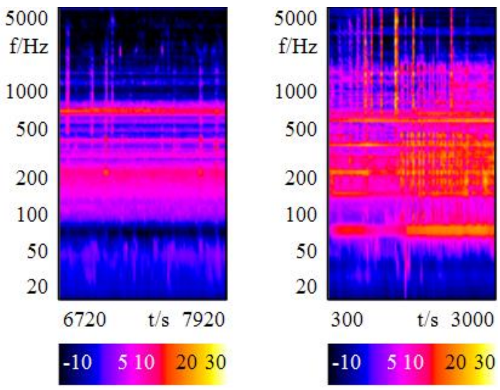

Figure 11. Spectrogram of the normal (left) and maximum (right) working condition of device 4 (A-weighted, spectrum size: 4096)

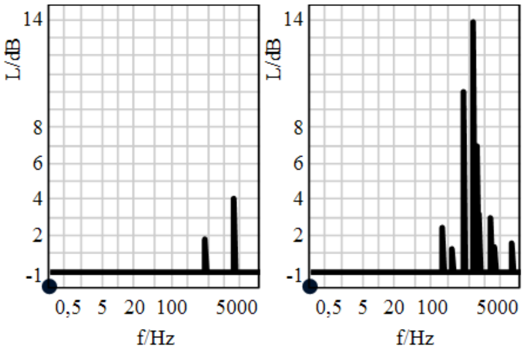

Figure 12. Tone-to-Noise ratio of the normal (left) and maximum (right) working condition of device 4

5. CONCLUSIONS

Study contained in this paper sheds the light on an aspect of household refrigerators operation, which is not typically attainable by customers. It started with a reference to recently created airborne acoustical noise emission classes [1], where the typical sound power levels span from below 30 to above 42 dBA. These conditions are limited however only to "steady-state" conditions of refrigerators operation [9] and authors argue that, for modern refrigerators, these conditions are almost inaudible to typical users [2]. Selected customer satisfaction analysis (based on 5-Star reviews [8]) demonstrated that end-users have some important comments related with how modern refrigerator devices work and sound they make in other conditions. With the measurements on some selected refrigerators from European markets (including specifically inverter refrigerators), authors have shown that the same device can have significantly different sound power level emission when working at its highest cooling capacity, in some cases up to 10 dBA (or a difference of two acoustical noise emission classes). Moreover, the loudness analysis shows that the difference between two extreme working conditions of the same device can contribute to the perception of being even up to 10 times louder. This is supported by significant increase in tonal character of the sound, especially at the high-end of inverter compressor working speeds.

These facts could be worrying for customers, who are especially searching for very quiet refrigerators to their homes. Looking solely at the only officially available data, in the form of Energy Label [1], one could be misled in their decision purchasing the product that can be quiet in some conditions, but highly annoying in others. This is important, given also how the inverter compressor works [6], where given operating speed is not driven by what user

selects, but by cooling algorithm based on temperature probe. The measured maximum working conditions can happen at random times, based on cooling load, when the user might not necessarily want it, creating dissatisfaction.
For this reason, authors are proposing that the information on the expected sound level emission during the product running at the maximum cooling capacity shall be requested from manufacturers and shared with customers in some way, for example, an additional place on Energy Label or at least a written statement in the technical documentation of the product. This would on one hand promote a design of overall quiet appliances (not only limited to a single condition), but also would enable a sound purchasing decision for sensitive clients that are searching for quiet emission under all situations.

6. REFERENCES

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