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COMPARISON OF CONTROL LOGIC DRIVING INVERTER COMPRESSORS IN REFRIGERATORS AND POTENTIAL IMPACT ON CUSTOMER SOUND QUALITY ASSESSMENT

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ABSTRACT

Acoustics and vibrations improvement developments in household appliances is usually based on basic Source, path and receiver problem solving model. The engineering sector has moved across the years from simple additions of acoustic or vibration damping materials (focused on path improvement) towards optimization of sound sources (like motors, for source improvement) where greater gains were possible. Notably, the latest and modern appliances take advantage of variable speed inverter motors, running at minimal speeds most of the time, producing little noise and vibration, resulting in very low sound power level claims on energy labels. Authors of this text found out however that the applied algorithms to control speed of inverter compressors on refrigerators can vary significantly. This study aims to compare various approaches from appliance manufacturers to control the speed of inverter compressors, targeting greater customer satisfaction once the product is running at end user premises. It engages also into a debate which algorithms are more favorable from developmental engineering perspective as well from final customer.

Keywords: *inverter compressors, household appliances, noise control, psychoacoustics, sound quality*

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1. INTRODUCTION

The research area of noise reduction in household appliances business, as well as adjacent businesses, is frequently modelled as “Source, Path and Receiver” [1]. In that model a source of noise is being considered a compressor or fan motor (in typical, simpler type of refrigerators [2]) as well as valves, gears, flow in tubes, etc. (in more efficient refrigerators). Since the primary goal of acoustic or noise reduction treatment is to not detriment the core function of a product (i.e. cooling in case of refrigerator), the majority of engineering interventions were focused on optimizing the path that leads from a source to receiver (i.e. microphone or final user). Typical ways of achieving this in refrigerators are additional rubber or viscoelastic components (or equivalently, bitumen or foam components in dishwashers). Since addition of these components has strong implications on cost of the product (serious concern for manufacturers), the producers of sources started to put more emphasis on the design of components, consequently moving the attention from path to source of the aforementioned model. The area of improvement is related to internal design of components, for example, compressors, such as internal tubing’s and suspension [3].

This paper analyzes another aspect of noise reduction engineering, related to the way the new type of inverter compressors are controlled in refrigerators. This is especially important, as according to information from suppliers [4], there are expected rather large differences in acoustic performance of inverter compressors when running at different speeds.

2. MOTIVATION

Authors of this text were motivated by the outcome of earlier studies [5], where survey participants were commenting how they perceive the noise of modern refrigerators at home. Especially the reflections on the responses to the questions "Can you particularly notice when the compressor works at high speed" and "How often do you notice that your refrigerator is working in high speed mode?" were worthy of further studies. Based on that survey, 43.4% of respondents indicated awareness of changes in the compressor operating condition in response to the question "Do you notice when the working condition of your compressor changes". It is a known phenomenon that human hearing is sensitive to small changes in sound [6], and since modern refrigerators are mostly equipped with inverter compressors (which changes speeds based on electronic system inputs), the motivation existed to measure how often that situation occurs in normal usage, what is the rate of change, how many different conditions are present, etc.
Authors suspected that this could be an area of differentiation between manufacturing brands, in an attempt to please its customers with a sound of product and avoid unnecessary annoyance and disturbances to achieve proper sound quality level. The experimental space of testing included various refrigerators' models from the European market, produced by locally available manufacturers. All of these were using inverter compressors.

3. MEASUREMENTS & ANALYSIS

3.1 Testing conditions

A key aspect was trying to obtain various working conditions of tested refrigerators. To achieve this goal the tested objects were put into two conditions:

- normal working mode, representing running explained in IEC 60704-2-14 standard [7] as "steady-state", where product is supposed to maintain the internal temperature with highly reproducible compressor running cycle
- first working mode, representing a situation as if a user would plug in the product for the very first time, where the product (initially warm) is supposed to start cooling down towards the desired nominal temperatures.

The idea behind the latter working mode is that authors expected the object would go through various modes along with the reduction of internal temperature. Indeed, later testing results proved the assumption, as it is revealed in the next sections.

3.2 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.

3.3 FFT spectrograms analysis

The FFT spectrograms below represent the vibrations obtained from the accelerometers mounted on compressors of three selected refrigerator models, each displaying a different method of controlling inverter compressor speed. Main emphasis in analysis is on tracing the vertical lines in frequency axis (x-axis), representing the changing fundamental frequency of compressor vibration, thus compressor speed. The next three spectrograms (Figures 1 - 3) represent first working mode cycles (as explained in 3.1) and the time span (Y-axis) covers the entire compressor running cycle, from the moment it was powered on until the natural stop (related to achievement of nominal temperatures) for three different brands. From the first look at the graphs, it is clear that the strategy of signal control is very different for each brand.

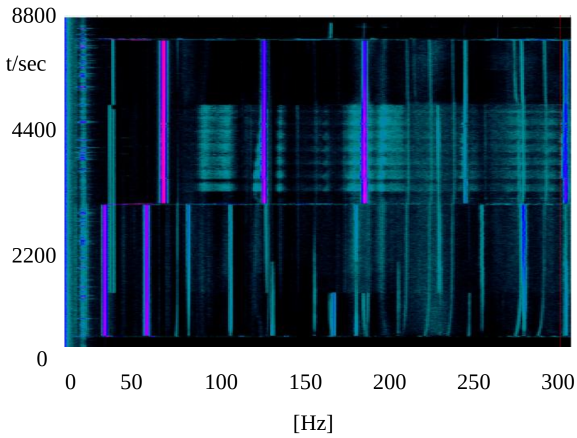

Figure 1. Vibration spectrogram of the first working mode, refrigerator brand 1.

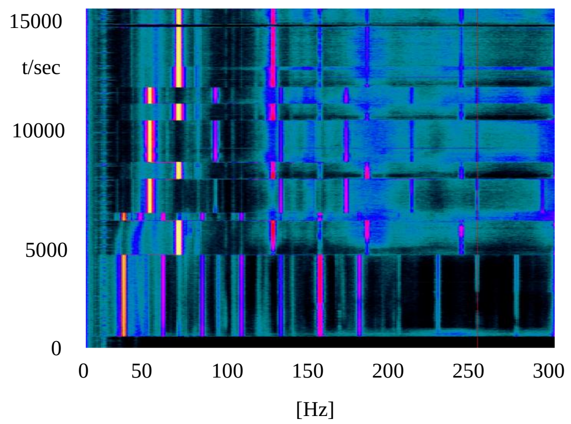

Figure 2. Vibration spectrogram of the first working mode, refrigerator brand 2.

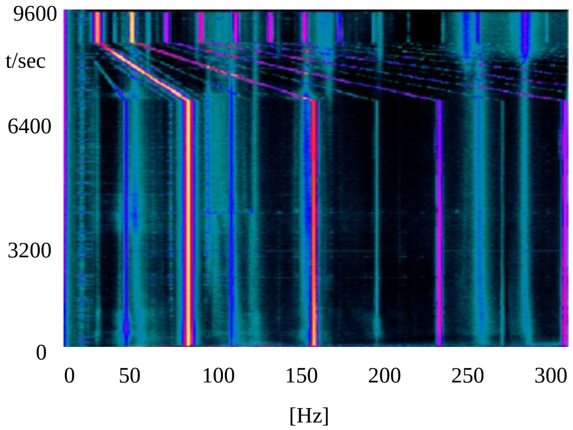

Figure 3. Vibration spectrogram of the first working mode, refrigerator brand 3.

Each brand has a different strategy engaging inverter compressors to cool down the product. Brand 1 is using just two discrete speed steps (lower fundamental frequency around 20 Hz corresponding to 1200 rpm, and higher frequency 60Hz, corresponding to 3600 rpm). Between these two, there is just one change in the middle of the running cycle (Figure 1).
On brand 2's refrigerator, the compressor is changing speed 8 times in the cycle. Time at each speed is unequal and three distinctive speed steps are distinguished (around 20, 40 and 60Hz, corresponding to, respectively, 1200, 2400 and 3600 rpm) (Figure 2).
The graph representing measures of brand 3 is again different. Again only 2 main speeds are detected (around 75Hz and 20 Hz, corresponding to 4500 and 1200rpm), but the majority of the time it works at first running speed, followed by a lengthy period of transition from initial speed to final speed (Figure 3). Figure 4 shows, zoomed in, the area of transition from one speed to the next with a highlighted time for brand 1.

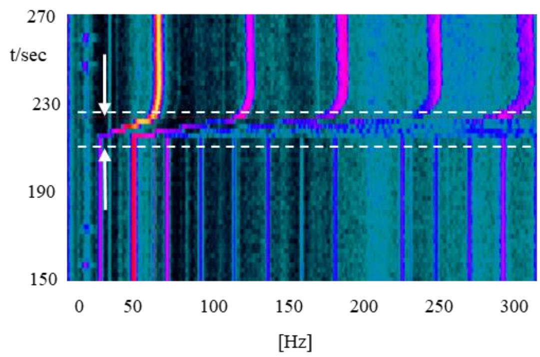

Figure 4. Vibration spectrogram of the area of transition from one speed to the next with the highlighted time for brand 1.

For each brand the respective time to transition between desired speeds was 60 seconds, 10 seconds and 18 minutes (respectively for brands 1, 2 and 3).Such varying transition times can have a significant impact on perceived sound quality, depending on the presence of structural resonances in the range of speeds selected. The next three spectrograms represent a different approach to speed control of the compressor during normal working mode (as in 3.1).

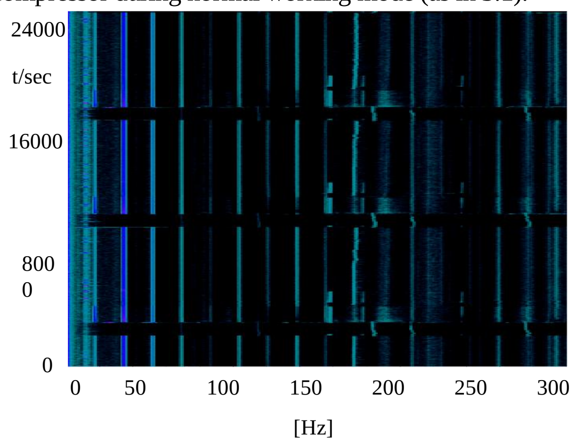

Figure 5. Vibration spectrogram of the normal working mode, refrigerator brand 4.

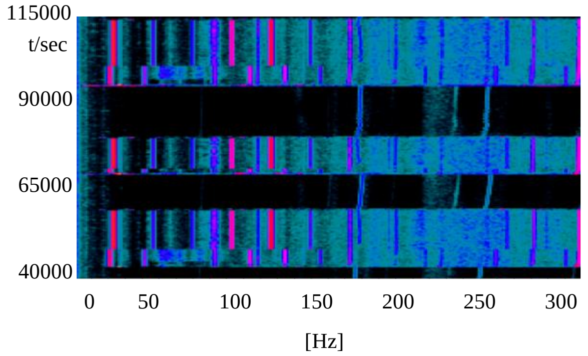

Figure 6. Vibration spectrogram of the normal working mode, refrigerator brand 5.

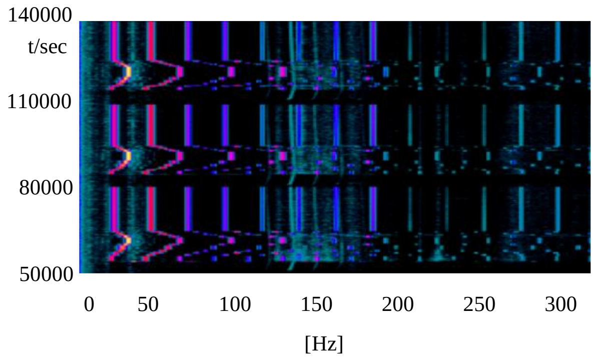

Figure 7. Vibration spectrogram of the normal working mode, refrigerator brand 6.

Compared to the first working mode, the normal working mode tends to engage only one compressor speed around 20Hz (corresponding to 1200rpm) for each of three brands, however still some noticeable differences between brands are present like either keeping one speed flat, changing sharply between two speeds or slowly modulating the speed close to the nominal.

3.4 Psychoacoustic analysis

The variation in compressor driving speed is primarily determined by the required cooling demand. Based on this demand, a specific RPM value is set. Accordingly, the compressor either accelerates from zero to reach this target speed (first working mode) or maintains a stable temperature by adjusting its speed accordingly (normal working mode). The decisions made at this stage—such as how quickly the compressor should reach the target RPM or which intermediate steps it should follow—significantly impact noise emissions and, to a large extent, psychoacoustic parameters. Different numbers of steps, varying frequencies (hence different RPMs), and different transition lengths all influence the compressor's operation. RPM changes can create BSR problems (buzz, squeak and rattle), lead to resonance issues, which not only elevate overall noise levels but also enhance tonal components, affecting the perceived sound quality.

To evaluate the various vibroacoustic issues that may arise from RPM changes and their corresponding psychoacoustic effects, a sample recording was analyzed. Figure 8 presents the spectrograms of this recording. The upper panel, plotted only up to 300 Hz with higher FFT resolution, focuses on better visualizing the compressor's operating conditions. In contrast, the lower panel displays all audible sound events. In this example, the compressor initially runs at approximately 60 Hz before gradually reducing its speed over an extended period. As expected, strong resonances can be observed during this deceleration phase, particularly in the lower panel as indicated by the yellow areas. Figure 9 presents a magnified view of the lower panel from Figure 8, providing a more detailed representation of time- and frequency-dependent sound events for better analysis.

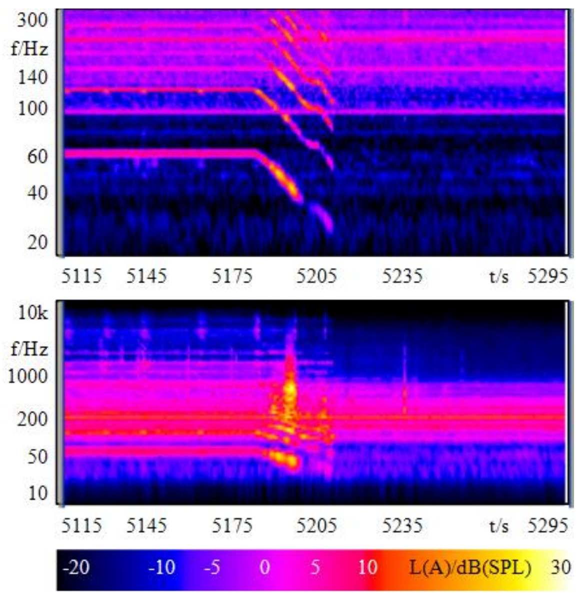

Figure 8. Spectrograms of an example compressor deceleration. (Upper panel spectrum size: 16384, lower panel spectrum size: 4096, A-weighted).

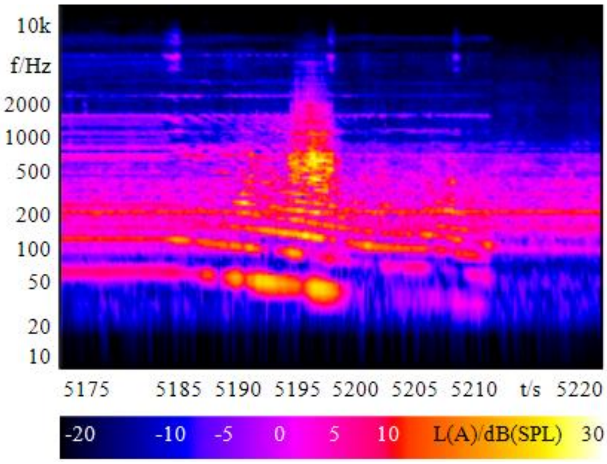

Figure 9. Spectrogram of an example compressor deceleration (detailed view of lower panel from Figure 8, spectrum size: 4096, A-weighted).

As expected, resonance issues arise during this transition, significantly degrading sound quality. Figure 10 illustrates the A-weighted sound level and the loudness level according to ISO 532 during this phase. Considering that these recordings were made in an anechoic environment—and that these values could be higher in a real room—it would not be incorrect to state that the refrigerator transitions from being "inaudible" to "noticeably disturbing" during this period [5]. Similarly, the hearing model tonality values during this resonance phase are presented in Figure 11. Even under anechoic conditions, the tonality values rise from very low levels to exceed the threshold value of 0.40 [8].

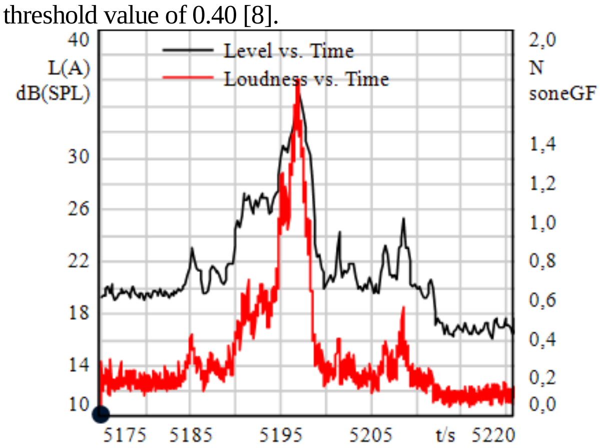

Figure 10. A-weighted levels and loudness levels (ISO 532) over time for the example case in Figure 9.

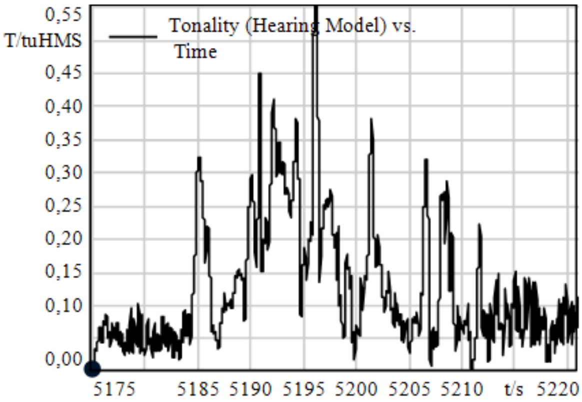

Figure 11. Hearing model tonality over time for the example case in Figure 9.

From this perspective, continuous and slow RPM changes can be considered detrimental to sound quality. The literature already suggests that compressors should operate in a stepwise manner rather than with continuous adjustments [9]. However, determining which RPM values should be used as steps becomes a challenging design problem, especially when considering the complex vibration transfer paths of the devices. Moreover, based on these specific insights on possible transfer paths, RPM steps and their durations should be selected and optimized for the particular characteristics of the device, ensuring better acoustic performance and reduced user annoyance. This approach demonstrates that significant improvements in sound quality can be achieved solely by modifying the compressor’s operating algorithm, without the need for additional materials or components. As a result, manufacturers can enhance acoustic performance without incurring extra costs, making this an efficient and cost-effective solution.

As a general rule, higher RPM corresponds to higher noise levels [2, 9]. In particular, high RPM can push a modern refrigerator from being inaudible to clearly perceptible noise levels [5]. Due to both noise concerns and energy consumption, lower operating speeds are typically preferred. However, in specific cases—such as newly stored groceries—algorithms often opt for much higher speeds. High RPM directly translates to higher sound levels, increased loudness, and potentially elevated tonality, all of which contribute to increased annoyance and reduced sound quality. As a trade-off, rather than using the highest RPM values, a moderate speed can be employed, as long as it does not significantly reduce cooling performance and speed. This selected RPM should not coincide with any resonance. In this way, a significant improvement in sound quality can be achieved with just an algorithm change.

Another important aspect is the speed at which transitions between defined RPM steps should occur. From a psychoacoustic perspective, two key points can be highlighted. While rapid changes are generally perceived as more disturbing and attention-grabbing, psychoacoustic evaluations focusing on product sound quality must also consider the operational context and user interaction. Although very short-duration changes may be noticeable, their low frequency of occurrence throughout the day reduces possible user exposure, ultimately contributing to a higher overall perception of sound quality. This hypothesis is based on initial observations and should be further investigated in future studies in controlled listening experiments.

From a control algorithm perspective, another factor that may not cause operational issues but can be highly detrimental to sound quality is the defined minimum RPM step size. Figure 12 provides an example illustrating this issue. This example presents the noise characteristics of a refrigerator, specifically detailing the 50–80 Hz range with high FFT resolution. As shown in this detailed view, the compressor undergoes very small speed variations, sometimes as little as 2–3 Hz. At this already high operating speed, the device's perceived noise level is elevated. One can argue that, even the elevated levels can be accustomed after some time as long as the stationarity can be achieved. However, this type of very small fluctuations can attract constant attention of the user, deteriorating the sound quality of the device. Ultimately, it can be argued that annoyance is, to some extent, linked to attention.

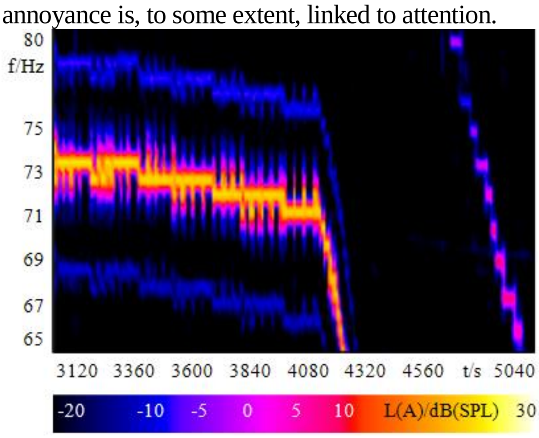

Figure 12. Spectrogram of an example refrigerator in the 50–80 Hz, illustrating small speed variations (2–3 Hz) of the compressor at high operating speeds (spectrum size: 65536, A-weighted).

4. CONCLUSION

The modern refrigerators, at the example of popular models from the European market, are built with inverter compressors [4]. These compressors usually have a significant range of speeds available and are an interesting challenge from acoustic and vibration-engineering standpoint. Authors have shown that although the majority of these products converged their claims (like on Energy Label, based on standardized conditions [7]) towards similar values, yet in practice, while running in a way similar to what end-users would experience, have substantial differences in control algorithms. These differences are related to how many different speed steps are used, how often they are engaged and how quickly the algorithm transitions from one to another speed.

The results show that speed changes have a significant impact on both sound levels and user perception (based on loudness and tonality examples). Therefore, optimizing the compressor's speed transitions, rather than just focusing on low RPMs (for the sake of Energy Label claim), is crucial for balancing effective performance with user satisfaction and preventing a poor overall product image.

In summary, as it was presented, the control algorithm adaptation becomes another interesting aspect of acoustic and vibrations optimization and a battlefield between the manufacturers trying to achieve customer greater satisfaction with the product. Consequently, manufacturers can improve acoustic performance without additional expenses, making it a practical and cost-efficient solution.

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