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Original Article

An automated diagnosis methodology for manufacturing and assembly failures of refrigerator compressors on production line using vibration data

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ABSTRACT

This paper presents, the design of a system that performs automated detection and diagnosis of several types of failure with time-frequency (Fast Fourier Transform) based analysis of vibration data taken from hermetic compressors used in home appliances. The objective of this paper is to investigate the vibration characteristic of noisy appliances and cooling faults. Experimental studies were conducted for finding the correlation between failures and vibration data. Vibration data of appliances for the various fault cases were collected and correlation was determined between the inputs and outputs with the help of regression analysis. The fault characteristic for the huge amount of time-frequency data was transferred into a central data lake on a cloud for fault classification. Thus, characteristic algorithm was applied to automate the production process. As a result of the study, it has been revealed that the noise level of the compressors used in refrigerators with 74.41% reliability can be calculated through the vibration sensor.

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INTRODUCTION

Professor William Cullen from Glasgow University in Scotland discovered a man-made cooling method for the first time by evaporating the ether in 1748. In 1755, when Professor William Cullen developed a simple and mechanical cooling system, the basis of today's refrigerators was revealed. When Jacob Perkins developed the first practical cooling machine in London in 1834 using a vapor compression cycle with ether, it also allowed the cooling industry to progress steadily [1].

In 1856, James Harrison laid the foundations of industrial refrigerant systems with his patent. S. Liebmann's Sons Brewing became the first company to use a fully mechanical cooling system in 1870. In the period up to 1891, many companies became using mechanical cooling systems [2].

When electricity became generally available, William F. Singer patented the first automatic electric unit used in small-sized refrigeration systems in 1897. Home refrigerators became very popular as electricity generation capacity grew, and homes began to be wired for electrical appliance use.

The interest and demand for home refrigerators were supported by the design and development of stepped horsepower engines used in refrigerators. The most important technical contributions were made by General Electric and Kelvinator companies. One of the first practical automatic controls was the thermostatic switch developed by Copeland for Kelvinator. The sealed unit, which eliminates the

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belt, was introduced by General Electric in 1925. These units began to be produced in large numbers in the early 1920s and became a must for everyone [3].

In the following years with the increase in electricity production, refrigerators with a similar system have taken their place in every house. Three types of cooling technology are used in the refrigerators produced today. These technologies are called static, no-frost, and static-no-frost hybrid. In the static cooling system, the evaporator is wrapped around the inner body of the refrigerator facing the outer body, and conducts cooling by conduction (conduction) by cooling the inner body surfaces. In these systems, icing occurs on very cold body surfaces.

In no-frost systems, the evaporator is in a closed chamber. The air-cooled in this chamber is transmitted from the air ducts to the refrigerator sections with the fan. Performing the cooling process in a closed chamber only causes ice to form in that area. The ice cooling process formed is melted by heating with a heater between them and transferred upon evaporation on the back of the refrigerator [4].

Although it is rare in the market; there are also refrigerators with no frost in the freezer part and static cooling technology in the cooler part. However, the use and production of such devices are very low due to the cooling cycle complexity and the cost increase caused by this complexity. Figure 1 shows a comparative depiction of static and no-frost cycles [5].

The economic growth rate, which has increased with the development of technology and science, is increasing the living standards of people day by day. Today, people attach great importance to the quietness of their living spaces, and the number of customers who complain especially in the white goods sector due to the loud operation of their devices is growing rapidly.

For manufacturers, sound insulation works that can be done for noise reduction both create extra costs and reduce the energy efficiency of the devices. Many studies have been carried out in this field and project phases until today.

In the study carried out by Guo et al. [6] to reduce the noise level caused by the compressor in the refrigerator aggregate area in 2015, the area was preserved with a metal sound insulation piece. The purpose of the study is to lower the noise level in the customer's home rather than separating the audio compressors in the production area. In his study by Dianov [7] in 2020, he revealed the character of the supply signal required for the compressor to stop quietly. In his study in 1999, Steffenato proved the correlation between the vibration data of the compressor in a system using R600a refrigerant and the noise level of the compressor [8]. As a result of the work of Bogdanovská et al. [9], they established a quality control gate that improves the rate of complaints of the system by 50% with the comparative analysis of R134a and R404a refrigerant gases.

Park et al. [10] worked on a vibration estimating model based on magnetic field forces in axial flux motors. Tsypkin [11] revealed the analysis of typical vibration problems of asynchronous motors and related fault catalogs in his study. In another study, Mais [12] shared the harmonic de-

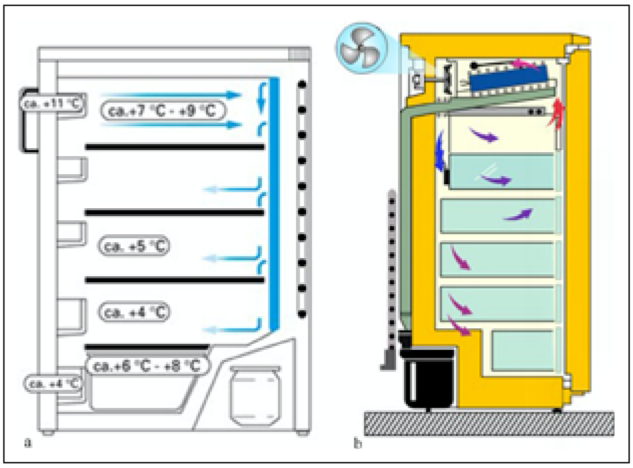

Figure 1. Comparative depiction of static **(a)** and no-frost cycles **(b)**.

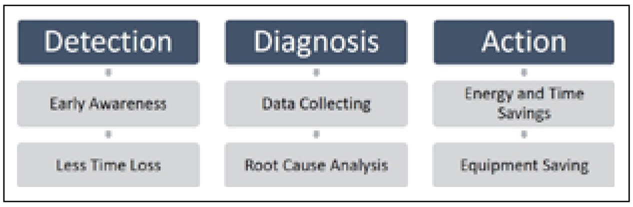

Figure 2. Three steps of AFDD.

composition in terms of rotating mechanisms and metrics of spectrum characteristics. Biernat et al. [13] analyzed the design process, suggesting possible additional changes in the stator, rotor geometry, and controller operation, minimizing the harmful vibroacoustic phenomenon. Jokic and Cincar's [14] studies; It has presented to the world of science with its study that failures on the rotor, stator, and other electric motor components, vibration measurement, and motor current signature analysis can be detected successfully. In another study, a digital pulse width modulation (PWM) based control technique was used to operate the brushless direct current (BLDC) motor experimentally to perform vibration and acoustic noise analysis [15]. The study of Alekseev et al. [16] performs fault diagnosis with analysis of vibration harmonics in Asynchronous motors. Industrial production systems are developing rapidly today. Along with this, the demand for quality and efficiency in production also increases, and the quality controls of the products gain importance. These inspections were performed very slowly and with low efficiency by human observation.

Today, automatic fault detection and diagnosis (AFDD) systems have the potential to reduce equipment downtime, service costs, and poor-quality costs. Figure 2 shows the three steps of AFDD. Placing these systems in the production areas not only increases the profit margin but also contributes greatly to brand reliability [17]. Behfar and his colleagues have worked on automatic error detection and diagnosis system that can detect and potentially use faults in refrigerators, lighting, and heating & cooling systems in supermarkets [18].

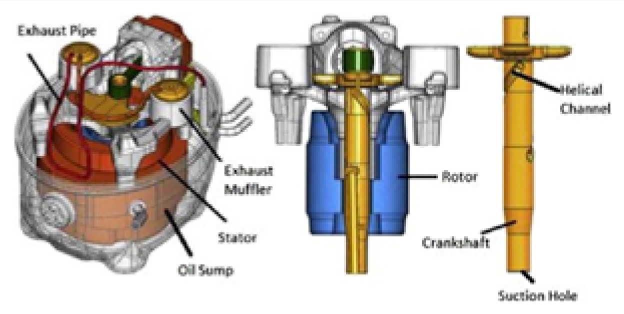

Figure 3. Compressor Components.

This system, which is the subject of the study, is an automatic failure detection and diagnosis system, and it provides reliable and fast control of all refrigerators on the production line where it is installed. The study aims to detect voice-operated refrigerators on the production line. The sound of the refrigerators depends on more than one variable.

These are sounds such as compressor operating sound, fan sound, and refrigerant gas flow sound. But among these, the compressor operating noise is much more important than others. On the other hand, determining the noise levels of the devices in factory environments is possible with long-term tests in rooms with high sound insulation. However, today, with increasing production speeds and quantities, and a very low rate of produced devices sound testing can be done in the sound room.

The compressor, which is the most noise-generating part of the parts used in refrigerators, is depicted in Figure 3 [19]. The compressor compresses the saturated refrigerant gas that draws the heat inside the refrigerator as it passes through the evaporator and raises it to high pressure and temperature. Saturated refrigerant gas, which rises to high pressure and temperature, passes to the plaster phase, and from this point onwards, the refrigerant gas becomes suitable for giving heat energy to the external environment [20]. In another study, it was tried to find the connection between the time and frequency-based analysis of the vibration data received in the Z-axis direction and the noise level via a refrigerator compressor [21].

In this study, a system that is fast, reliable, and able to test the noise level of the refrigerators on the conveyor line in the production area has been studied.

MATERIALS AND METHODS

The system application was carried out on the conveyor belt in the refrigerator production line. Thus, the system will automatically send a signal to the "PLC (Programmable Logic Controller)" which controls the conveyor belt in the production line, and the noisy appliances can easily be detected by separating from the belt. The measurement is taken because of the presence sensor being stopped and triggered at the point specified in the conveyor and the sensor is left in the compressor for 20 seconds using the collaborative robot.

Figure 4. The robotic arm and sensor positioning.

Table 1. Sensor specifications

Measuring condition	Operating range
Frequency Range	0.2–12.800 Hz
Temperature	-55 to +125 °C
Weight	8.6 gram
Sensitivity	1 mV/ms^{-2}
Residual Noise Level	500 µg
Maximum Operational Level (peak)	714 g
Resonance frequency	38 kHz
Maximum Shock Level (± peak)	10.000 g

An interface electronics is used to process the signal and inside of the electronic "TMS320C33" 120 MHz (Megahertz) power signal processor is available. The measurement frequency and processing range are between 10 Hz and 40 kHz.

The accelerometer sensor specifications are given in Table 1 [22].

As the conveyor control unit, the vibration measurement interface electronics, and the robot are integrated, the sensor allows it to move only through the compressor after the measurement is completed when the measurement ends.

In experimental measurements, the system and sensor position is positioned in the direction of the Z-axis as in Figure 4, and all measurements are carried out on this axis with the same type of compressors.

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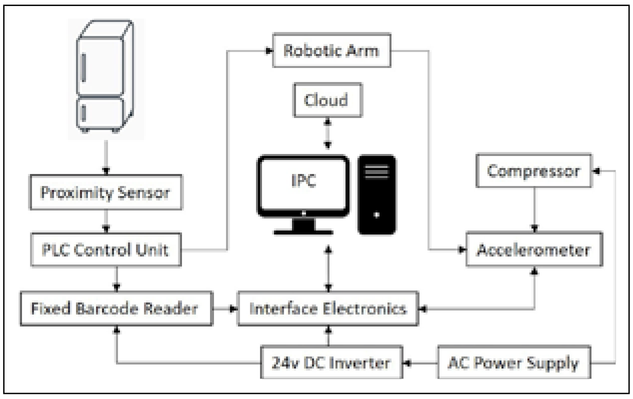

Figure 5. Flow chart of the experimental system.

Table 2. Refrigerator aggregate zone components

No	Component
1	Run Capacitor
2	PTC
3	Evaporating Cape
4	Compressor
5	Accelerometer
6	High-Pressure Tube
7	Low-Pressure Tube
8	Dryer
9	Condenser Tube

Figure 5 shows the system flow diagram and conversion of analog data to digital. It simply shows the process of analyzing the vibration data characteristic of the refrigerator compressor in the computer environment.

The interface depicted in Figure 6 is the frequency inspection screen on this program. The data-frequency range collected from the compressors that constitute the subject of the study is between 10 Hz–1.5 kHz. The software reveals acceleration values up to 1.5 kHz in the graphics on the user interface. On the other hand, the electronics used in the project assumed the task of converting the data into digital so that analog data flowing through the sensor can be processed in a virtual environment. So that the spectrogram which is shown in Figure 6, becomes the main point of industrial purposes of noise investigations. Thanks to the limit entering feature provided by the program, when the result is observed other than the entered values, the output, i.e. "PLC", can be output to be sent to the control unit. For the experimental study, 40 devices taken from the same production line were analyzed in the spectrogram program by taking vibration measurements on the compressors.

The aggregate area and other components that constitute the subject of the study are depicted in Figure 7, the component information is shared in Table 2. The compressor vibration data from the subject of the study was obtained with the help of the accelerometer.

Theory

The system is based on transmitting to the interface electronics as the "V" (Volt) of pressure change occurring on the accelerometer surface in line with the oscillation of the compressor.

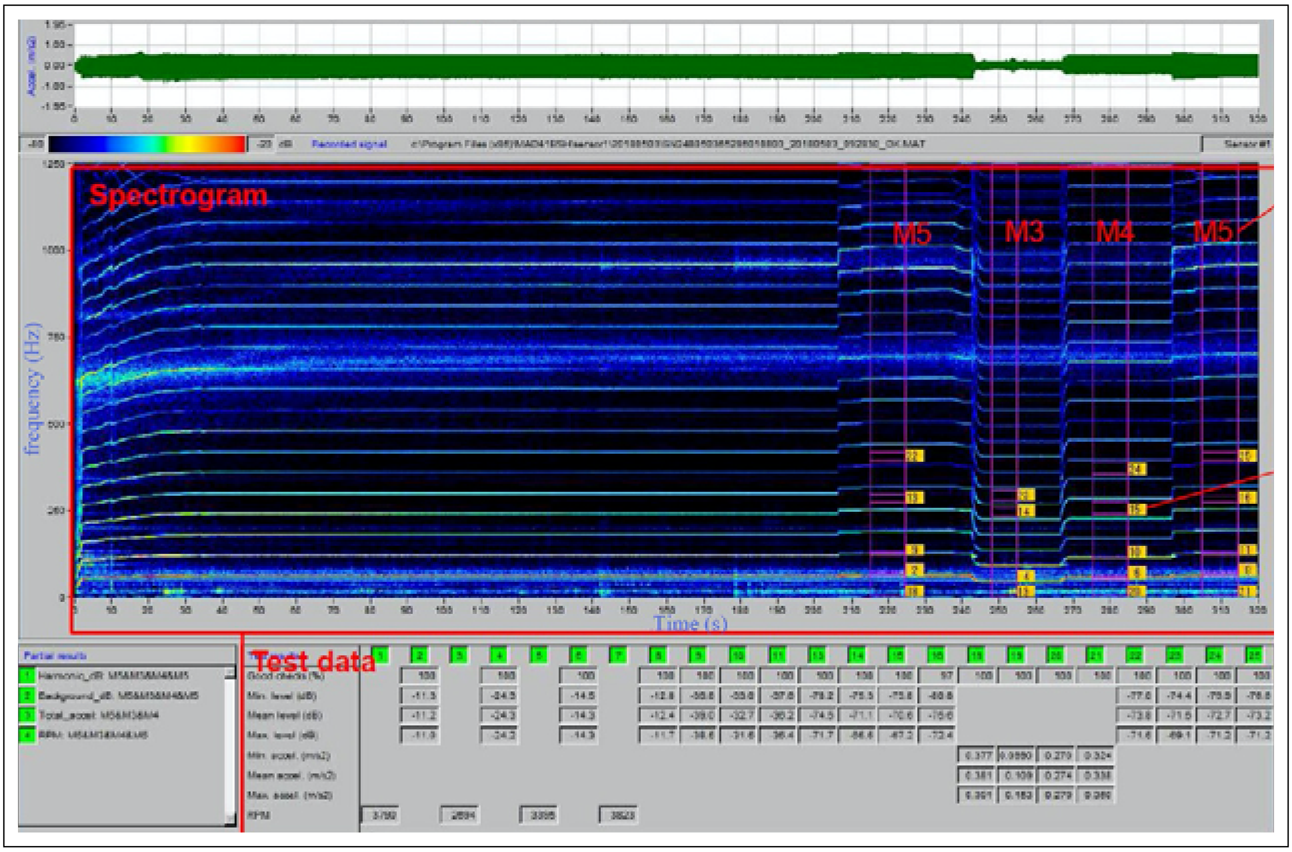

Figure 6. The interface of vibration analysis of variable speed compressor.

The correlation between “V” and “a” (Acceleration) (m/s^2) is obtained by dividing the average of the square roots of the “V” values read from the sensor into a coefficient “C” connected to the sensor [23].

$$\frac{\frac{V_1+V_2}{2*C}}{\sqrt{2}} = \alpha \quad (1)$$

In the software, the square root mean values of the acceleration are logarithmically compressed from 0 dB to -80 dB, and the calibration of the sensor was chosen as the reference point.

"a_0= 0.00089 m/s^2= -78 dB" the lowest point received. As the accelerometers are approached to take measurements at frequencies close to the resonance frequency, the possibility of taking an incorrect measurement increase. In measurements taken up to one-third of the resonance frequency of the accelerometer, the error rate can be up to 12% [24]. The accelerometer resonance frequency used in the project is specified in Table 1. The fact that a value less than -80 dB appears in the spectrum or that no value close to -80 dB appears in the spectrum indicates that the sensor is taking an incorrect measurement.

In this context, for every “20 dB” (Decibel) increase on the spectrogram, the acceleration value will increase 10 times its initial value.

$$a=a_0 \times 10^{(dB \div 20)+3.9)} \quad (2)$$

The acceleration value of the obtained vibration can be read by decomposing it into harmonics with the help of the Fast Fourier Transform (FFT). The first three harmonics of this acceleration are called A, B, and D harmonics, B, and D are multiples of A harmonic (Base Harmonic) shown in Figıre 8. Harmonic B is the vibration oscillation of the compressor in the second fold of the operating frequency, and the D point in the tertiary fold.

The system software also enables the compressor operating speed to be measured. This speed can be defined on the limit screen to the first harmonic (compressor base operating frequency) in the frequency graph depicted on the interface. The relationship between the first harmonic (point A in Fig. 8) and rpm (round per minute) is as in formula 3.

$$rpm=1_{st}\ Harmonic\ (Hz) \times 60 \quad (3)$$

The last value measured on the program used in the calculation of the compressor noise level is the effect of the magnetic field generated by the induction motor on the accelerometer sensor. This effect in the work of Shin and Choi [25] is an example of the project. The effect of the magnetic field at this point can be seen on the spectrogram at the frequency and its multiples where the frequency of the alternating current is multiplied by 2. The oscillation of the effect of the magnetic field on the accelerometer on the 100 Hz band is shown as point C in Figure 8 and point E in Figure 8 at 200 Hz.

It is possible to enter the limit range for the acceleration values calculated by the program from the sensor measurements. Acceleration values are capable of automatically calculating the lowest, highest, and average “dB” values in the frequency graph, saving the automatic measurement result from the computer to the given file location or transferring it to the cloud.

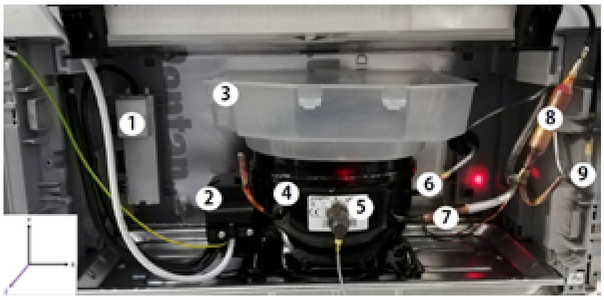

Figure 7. Refrigerator aggregate zone and possible vibration points.

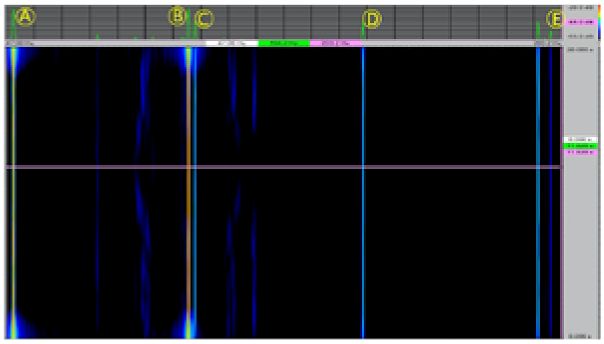

Figure 8. Vibration spectrum.

Predictive Model

Minitab is statistical software that often comes together with the implementation of Six Sigma, CMMI (Capability Maturity Model Integration), and other statistical-based process improvement methods. Minitab is an easy-to-use statistics program that can perform a wide range of statistical tasks. The tools of this program can be used in all analysis phases of the 6 Sigma methodology. There are many studies and examples with the same mentality in this field. With these methods, Chang et al. [26] worked on a model that predicted the frequency fluctuation that occurred when the generator was switched off with inputs such as system load, season, and run time. Pereira et al. [27] Analyzed customer satisfaction in product design and development with Six Sigma. In a similar study, Park et al. [10] developed a noise-estimating model for axial flux motors. Costa et al. [28] removed and analyzed error breaks using the Six Sigma Pareto methods in the quality improvement process of pin placement on the electronic circuit.

In all analyses in the study, the stage of finding the correlation between noise level and vibration data was determined by analyzing this statistical program, and the collected data. In these analyses, with the vibration data of 40 devices; The relationship between refrigerator noise level “dB (A)”, which is one of the following input variables, has

Table 3. Sound and vibration measurement data

Ref. No	rpm	2. Harmonic (dB)	3. Harmonic (dB)	100Hz (dB)	200Hz (dB)	Measured dB(A)
1	2950	-45	-50.7	-32	-61	36.3
2	2957	-36	-48	-40.5	-64	36.5
3	2960	-33	-45.3	-32	-67	36.6
4	2950	-35	-48.4	-45	-58.5	36.6
5	2951	-34	-49.3	-42.5	-63	36.7
6	2950	-30.5	-53.8	-42	-59	36.9
7	2950	-29	-46.5	-38.5	-61.5	37.2
8	2966	-39	-51.2	-44	-65	37.3
9	2955	-33.5	-50.5	-45	-62	37.4
10	2953	-37	-48.4	-44	-58	37.4
11	2950	-32.5	-47	-41.5	-63	37.4
12	2957	-31.5	-44.8	-42	-62	37.6
13	2947	-31	-46.5	-43	-62	37.6
14	2956	-36	-55.2	-47	-63	37.7
15	2950	-33	-51.6	-41	-59	37.8
16	2950	-32	-44.8	-39	-61	38
17	2957	-39.5	-53	-34.3	-57.5	38.1
18	2963	-36.5	-44.8	-45	-69	38.2
19	2963	-35	-47.4	-48.5	-67	38.2
20	2955	-35.5	-43.7	-46	-65	38.3
21	2942	-28.5	-45.1	-49	-59.5	38.4
22	2940	-31.5	-50.2	-40	-62	38.7
23	2953	-27	-54	-37	-70	38.8
24	2946	-32	-46.7	-40	-60	38.9
25	2957	-31.5	-47.2	-41	-62	39.3
26	2946	-32	-46.7	-44	-65	39.3
27	2958	-39	-48	-43	-58.5	39.5
28	2930	-25	-46	-38	-60	39.6
29	2968	-32	-47.4	-54	-65	39.8
30	2935	-45	-46.5	-35.5	-62	39.9
31	2925	-32	-45.8	-48	-60	39.9
32	2930	-30	-49.1	-42.5	-56	39.9
33	2947	-28	-46.2	-38	-61	41.1
34	2955	-26	-54	-47	-56	42
35	2943	-28.5	-47.2	-39.5	-57	42.7
36	2925	-23	-42.7	-39.5	-59	42.7
37	2940	-27	-44.6	-39	-67	42.7
38	2946	-38.5	-44.4	-32	-60	43.3
39	2948	-27	-49.1	-37	-59	43.6
40	2952	-30	-44.4	-39	-60	43.8

been tried to be reached. The input variables mentioned above are analyzed on software and their mathematical values are collected in Excel format. The collection of these values was completed by measuring the noise level in the laboratory conditions of 40 refrigerators. The measurement results are given in Table 3. The noise level measurement screen example is shared in Figure 9. The input variables mentioned above are analyzed on software and their mathematical values are collected in Excel format. The collection of these values was completed by measuring the noise level in the laboratory conditions of 40 refrigerators. The noise level measurement screen example is shared in Figure 9.

In Table 3, the inputs used in the calculation of dB(A) obtained from the vibration data and the dB(A) values measured in the sound room are given numerically.

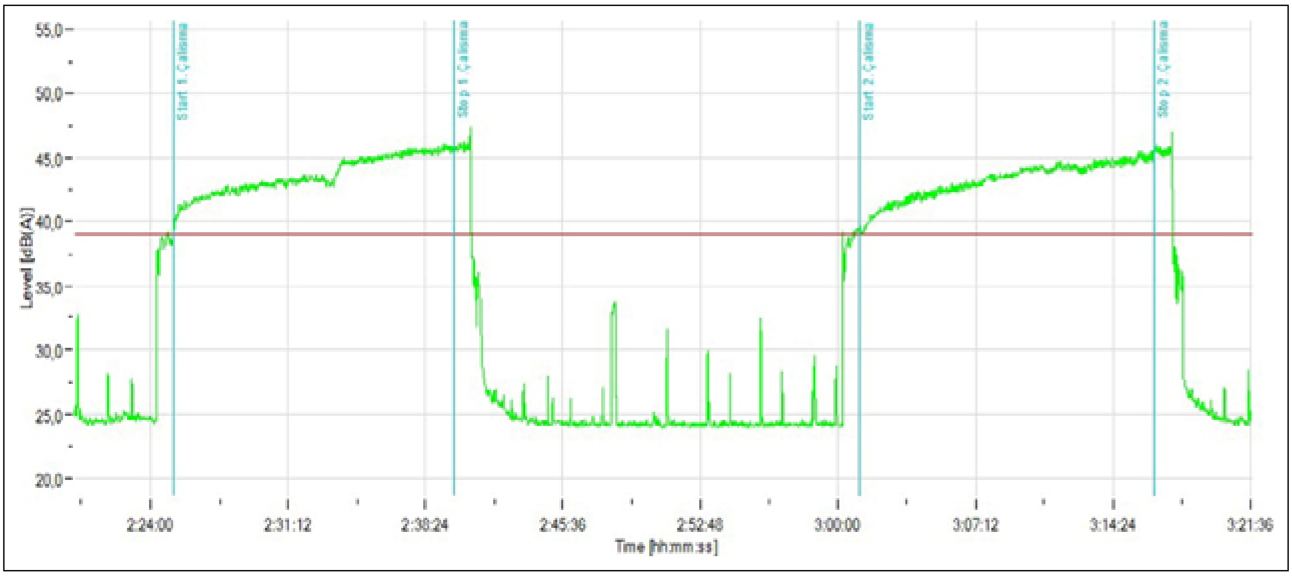

Figure 9. Example of refrigerator noise measurement.

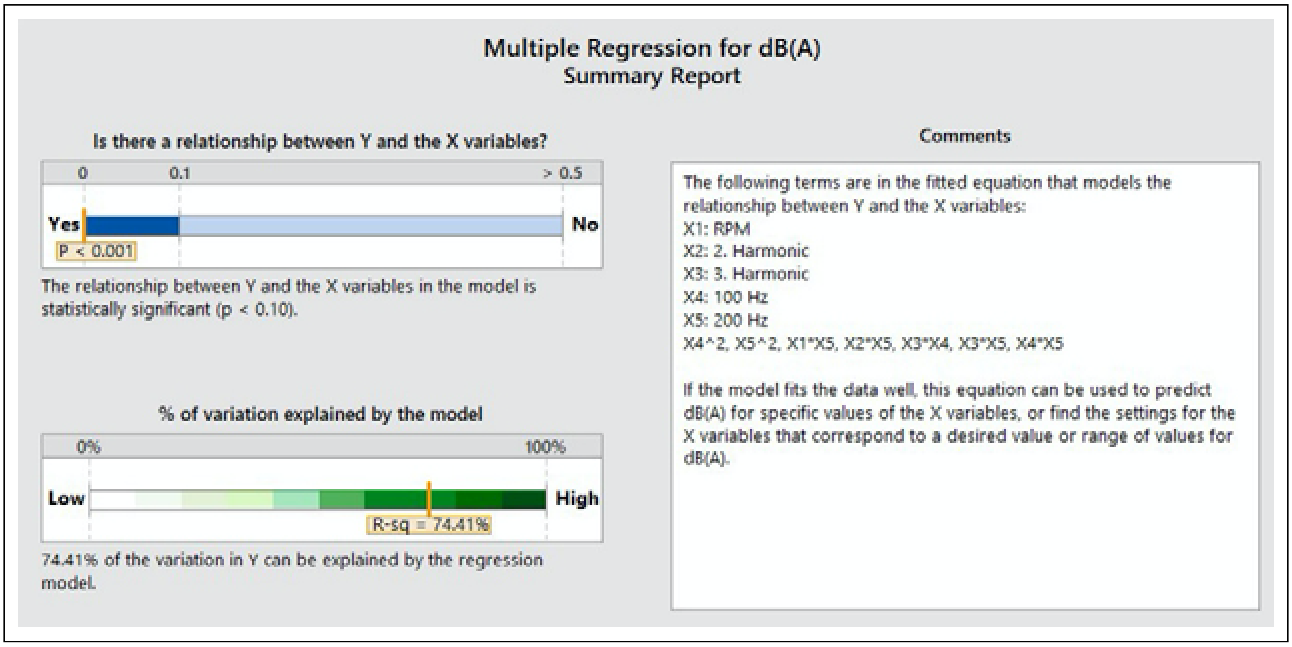

Figure 10. Summary report of regression analysis.

As a result of the regression analysis given in a summary report in Figure 10, a prediction model shown in Equation 4 is created. The dB (a) values were calculated with the prediction model.

$$dB(a) = -6872 + 2.6861^{*}A + 3.05^{*}D + 5.66^{*}E + 7.88^{*}B - 110.5^{*}C + 0.01892^{*}(B^2) + 0.1104^{*}(C^2) + 0.0446^{*}A^{*}C + 0.0485^{*}D^{*}C + 0.0446^{*}E^{*}B + 0.059^{*}E^{*}C + 0.0663^{*}B^{*}C$$

RESULTS

Considering the findings of the study, the following results have emerged.

- From the interference data, it has been demonstrated that the noise level to be created by a refrigerator produced in the production line under suitable ambient conditions can be estimated with an average of ±0.9 dB(A). These data are compared in the graphic in Figure 8.
- The noise level measured by the microphone and the values calculated by the predictive model determined by this study are presented in Table 3. It was observed that the rpm value measured by the accelerometer of a rotating closed asynchronous motor was directly related to the noise level created by the device. In line with the capacity of the engine, it was observed in the analyses that the noise level decreased as the number of revolutions increased.
- The lines depicted in the graph in Figure 11 show the comparison of the measured measurement results with the measured noise level in the sound room. The

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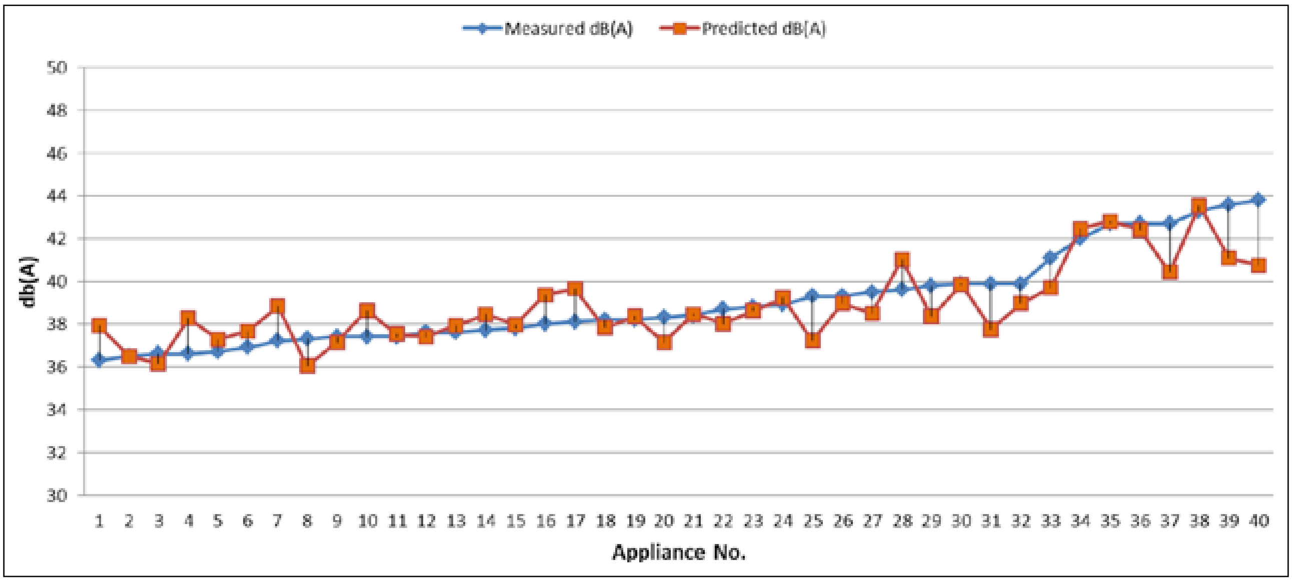

Figure 11. Comparison of dB (A) predictive model and sound chamber measurement results

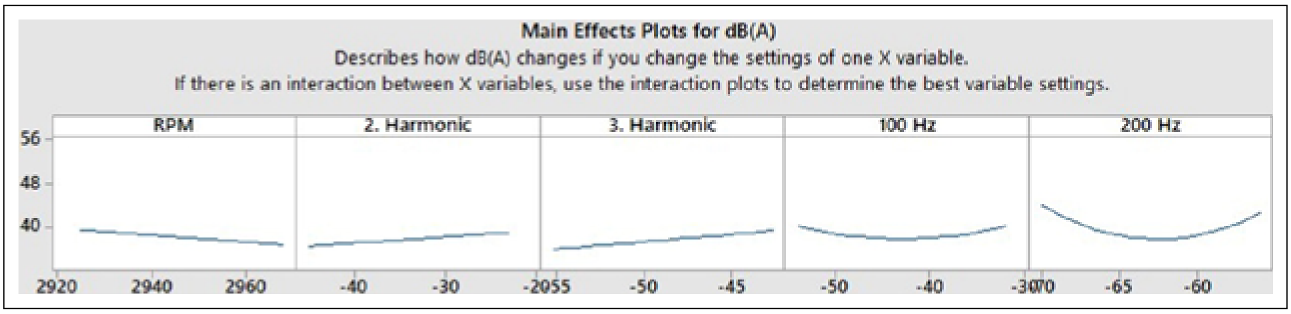

Figure 12. Relationship of vibration inputs with dB (A).

turquoise colored line represents the measurement results of the device in the sound chamber under laboratory conditions, and the orange color represents the noise level results obtained from the vibration data measured in the production area with the help of the predictive model.

- In the input variables bearing the subject of the study, it was observed that the sound level was directly proportional to the increase of the second and third harmonics in the vibration harmonics created by the compressor.
- For the fridge compressor and asynchronous motors, the value created by the force generated by the magnetic field on the accelerometer in the 100Hz band is between -40 and -50 dB, and the lowest value is dB (A).
- At 200Hz, this situation is between -60 and -65 dB, while dB (A) gets the lowest value.

The interaction rates of the input variables specified in Figure 12, respectively, with dB (A);

- Compressor rpm **(57.57%)**
- The amplitude of the signal at 100 Hz **(52.61%)**
- The amplitude of the signal at 200 Hz **(46.02%)**
- The Second Vibration harmonic value **(39.06%)**
- The Third Vibration harmonic value **(32.35%)**

CONCLUSIONS

As a result of the study, due to the noise and intense flow in production conditions, a quality door was added to the production line, which could not be established or predicted before, providing sound level measurement. In this way, it is possible to have information about the noise level of the refrigerators in the production area with simple vibration data.

The noise level of the refrigerator was calculated with an average deviation of approximately ± 0.9 dB (A) with a 75% reliability in the production area with the vibration measurement taken from the Z-axis from a hermetic compressor operating with an asynchronous motor that lasts for twenty seconds and rotates at a nominal speed.

Experimental work should be repeated for different model compressors and parameters should be determined again. In cases where the number of parts used is very diverse and quality control is done with sampling, sampling quality can be increased by using more general parameters.

The system can also catch this error due to abnormal increases in acceleration values in case of occlusion at some welding points in certain areas of the refrigeration cycle.

The system can also be used with different parameters on other devices, such as laundry care, whose noise source is moving mechanisms.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Ali Aykan Solmaz: Investigation, analysis, validation, original draft.

Alperen Acar: Methodology, review, editing.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Radermacher, R., & Kim, K., (1996). Domestic refrigerators: recent developments. *International Journal of Refrigeration, 19*(1), 61–69. [CrossRef]

[2] Boyacı, S., Ekren, N., & Görgülü, S., (2019). Test system design for automatic fault detection of electromechanical components used in refrigerators. *International Journal of Engineering Design, and Technology 1*(2), 42–50.

[3] Oldham, B. C. (1947). Evolution of machine and plant design. Proc. *Institution of Refrigeration 43*, 59–82.

[4] ASHRAE. (2018). *Refrigeration Handbook (SI Edition).* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

[5] Tezcan, A. (2018). *Modelling and optimization of double cycled condenser where is used on built in refrigerators [Master Thesis].* Trakya University, Institute of Science.

[6] Guo, J., Luo, J., Guo, Y., Pan, X., Fang, X., & Wu, X. (2015). Noise test and control for household refrigerator compressor. *IEEE International Conference on Information and Automation, August 8–10, 2015 Lijiang, China.* [CrossRef]

[7] Dianov, A. (2020). Estimation of the mechanical position of reciprocating compressor for silent stoppage. *IEEE Open Journal of Power Electronics 2*, 64–73. [CrossRef]

[8] Steffenato, S., Marcer, M., & Ayllon, P. O. (1999). Correlation between refrigerator noise and compressor vibrations development of a new measurement method for compressor vibration. *Sixth International Congress on Sound and Vibration July 5–8, 1999 Copenhagen, Denmark.*

[9] Bogdanovská, G., Molnár, V., & Fedorko, G. (2018). Failure analysis of condensing units for refrigerators with refrigerant R134a, R404A. *International Journal of Refrigeration 100*, 208–219. [CrossRef]

[10] Park, S., Kim, W., & Kim, S. (2014). A numerical prediction model for vibration and noise of axial flux motors. *IEEE Transactions on Industrial Electronics, 61*(10), 5757–5762. [CrossRef]

[11] Tsypkin, M. (2014). Vibration of induction motors operating with variable frequency drives - a practical experience. *IEEE 28th Convention of Electrical and Electronics Engineers in Israel (IEEEI), December 3–5, 2014 Eilat, Israel.* [CrossRef]

[12] Mais, J. (2002). *Spectrum analysis: The key features of analyzing spectra.* Accessed on Jan 21, 2020. https://www.skf.com/binary/tcm:12-3997/CM5118%20EN%20Spectrum%20Analysis .pdf

[13] Biernat, A., Jackiewicz, K., & Bienkowski, K. (2017). Vibration analysis of SRM designed for motoring and generating operation with spread spectrum current control. *19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe). September, 11–14, 2017 Warsaw, Poland.* [CrossRef]

[14] Jokic, S., Cincar, N., & Novakovic, B. (2018). The analysis of vibration measurement and current signature in motor drive faults detection. *17th International Symposium Infoteh-Jahorina (Infoteh). March 21–23, 2018 East Sarajevo, Bosnia-Herzegovina.* [CrossRef]

[15] Pindoriya, R.M., Mishra, A.K., Rajpurohit, B.S., & Kumar, R.V. (2018). An analysis of vibration and acoustic noise of BLDC motor drive. *IEEE Power & Energy Society General Meeting (PESGM)*, 05-10 August 2018. [CrossRef]

[16] Alekseev, V. V., Kalyakin, I. V., Konovalova, V. S., Konovalova, P. G., Perkova, & A. G., (2015). Diagnostic features identification algorithm according to vibration parameters of a compressor installation. *XVIII International Conference on Soft Computing and Measurements (SCM'15)*, May, 19 – 21, 2015 St. Petersburg, Russia. [CrossRef]

[17] Turgut, Y. (2013). *Machine vision based automatic fault control system. [Master Thesis]* Marmara University, Institute of Pure and Applied Sciences.

[18] Behfar, A., Yuill, D., & Yu, Y., (2017). Automated fault detection and diagnosis methods for supermarket equipment (RP-1615). *Science and Technology for the Built Environment, 23*(8), 1253–1266. [CrossRef]

[19] Zhao, J., Li, H., & Wang, S. (2013). Failure causes and countermeasures analysis for a large-scale reciprocating compressor vibration. *International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering (QR2MSE), July 15–18, 2013 Chengdu, China.* [CrossRef]

[20] Ozsipahi, M., Cadirci, S., Gunes, H., Sarioglu, K., & Kerpicci, H., (2014). A numerical study on the lubrication system for a hermetic reciprocating compressor used in household refrigerators. *International Journal of Refrigeration 48*, 210–220. [CrossRef]

[21] Tang, M., Zou, M., Wang, M., & Tian, C. (2018). Fourier series analysis applied in linear compressor

vibration analysis. *IEEE International Conference on Mechatronics and Automation (ICMA'18), August 5–8, 2018 Changchun, China*. [CrossRef]

[22] BKSV. (2020). *Product data*. Accessed on Feb 15, 2020. https://www.bksv.com/media/doc/bp2464.pdf

[23] Lally, J. (2020). Accelerometer selection consideration charge and integrated circuit piezoelectric. Accessed on Feb 10, 2020. https://www.pcb.com/contentstore/MktgContent/LinkedDocuments/Technotes/TN-17_VIB-0805.pdf

[24] Brüel & Kjaer. (1982). *Measuring vibration*, Accessed on Feb 29, 2020. https://www.bksv.com/media/doc/br0094.pdf.

[25] Shin, H. J., Choi, J. Y., Park, H., & Jang, S. M. (2012). Vibration analysis and measurements through prediction of electromagnetic vibration sources of permanent magnet synchronous motor based on analytical magnetic field calculations. *IEEE Transactions on Magnetics 48*(11), 4216–4219. [CrossRef]

[26] Chang, R.F., Lu, C.N., & Hsiao, T.Y. (2005). Prediction of frequency response after generator outage using regression tree. *IEEE Transactions on Power Systems, 20*(4), 2146–2147. [CrossRef]

[27] Pereira, M. T., Inês Bento, M., Ferreira, L. P., Sá, J.C., & Silva, F. J. G. (2019). Using six sigma to analyse customer satisfaction at the product design and development stage. *Procedia Manufacturing, 38*, 1608–1614. [CrossRef]

[28] Costa, J. P., Lopes, I. S., & Brito, J. P. (2019). Six Sigma application for quality improvement of the pin insertion process. *Procedia Manufacturing, 38*, 1592–1599. [CrossRef]