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EVALUATION OF SOUND QUALITY IN FAULTS OF SINGLE-PHASE INDUCTION MOTORS GENERATED IN A MANUFACTURING PROCESS

Gabriel Brandão Santos
Erasmo Felipe Vergara Miranda
Laboratory of Vibrations and Acoustics - Federal University of Santa Catarina - Florianópolis, SC, Brazil
gabriel.brandao@lva.ufsc.br, e.f.vergara@ufsc.br

Danilo da Silva Toniato
Laboratory of Vibrations and Acoustics - Federal University of Santa Catarina - Florianópolis, SC, Brazil
danilotoniato@hotmail.com

Henrique Alende da Silveira
Laboratory of Vibrations and Acoustics - Federal University of Santa Catarina - Florianópolis, SC, Brazil
henrique.alende@posgrad.ufsc.br

Abstract. *This study investigated the behavior exhibited by sound quality metrics obtained from single-phase induction motors under four different operating conditions, consisting of motors with three types of commonly found manufacturing faults in end-of-line tests from a manufacturer, as well as non-defective motors. 213 motors spanning the four groups were selected from this manufacturer. For each condition, a sample with a specific number of motors was taken. Sound quality metrics like loudness, sharpness, fluctuation strength, roughness, Aures tonality, and prominence ratio (PR) were calculated. The results were statistically evaluated to characterize the samples from each condition and assess their distribution and dispersion. The metrics responded differently to the conditions, with bracing tape faults showing higher average content of loudness and sharpness, the flawless motor standing out with more expressive quantities of tonality-related metrics, and bearing faults being well characterized by roughness. Most of the metrics calculated for lacing cord faults presented intermediate results. Non-parametric tests were applied to determine if the differences found between the groups are statistically significant and can be generalized to the representative populations of each condition. The study led to the conclusion that the metrics can distinguish the analyzed conditions, making them attractive for application in automated methods for diagnosing faults in the types of motors investigated in this research.*

Keywords: *sound quality, electric motors, psychoacoustics, fault detection.*

1. INTRODUCTION

Sound quality metrics have wide application in the assessment of psychoacoustic annoyance caused by product noise, as well as in the development of models that establish correlations between them and specific attributes perceived by consumers in the sounds of a given item. However, in recent works, these features have been successfully applied to fault detection and classification. Kane and Andhare (2019) fed artificial neural networks (ANNs) and support vector machines (SVMs) with loudness, sharpness, fluctuation strength, roughness, and tonality to detect faults in gearboxes. An automated classification method for five bearing operating conditions was developed using the same metrics (Mian *et al*., 2022). Murovec *et al*. (2020) developed a decision-making algorithm for detecting cavitation in centrifugal pumps using loudness, containing as output three pump conditions.

In all these studies, the mentioned metrics were obtained from carefully recorded sound samples, allowing the extraction of information that characterizes fault presence from a perspective focused on auditory sensations, unlike some traditional methods that use only physical evaluations of sound and vibration signals. In the case of electric motors, specifically in the detection of manufacturing faults during end-of-line inspections, auditory perception is taken into consideration through listening to motor sounds by operators who, based on their experience with acoustic characteristics, decide whether to accept or reject them. However, the subjectivity involved in this process necessitates the search for resources that harness the discrimination potential provided by hearing while introducing increased objectivity.

Thus, since sound quality metrics aim to objectively measure listeners' auditory sensations in response to physical stimuli (Zwicker and Fastl, 1999), they become potential candidates. The auditory differentiation by operators suggests the assumption that such features may respond differently to noises under various operating conditions of electric motors. This assumption motivated the investigation conducted in this study regarding the behavior of the metrics in four operating conditions of single-phase induction motors, which are subdivided into motors with three types of faults commonly found in end-of-line tests of a manufacturer and the non-defective condition.

Failures in the bearing and two components located in the stator, namely the lacing cord of its coils and the bracing tape, were investigated. Understanding how metrics respond to each condition enables the identification of those that most clearly characterizes each state, providing insight into how they might be exploited in future classification methods or which ones have a higher chance of correlating with attributes that can be perceived in the noises of these conditions in subsequent listening tests. Previous work used statistical procedures to evaluate metrics behavior for a variety of products or conditions.

Vieira *et al.* (2019) analyzed the variability of basic sound quality metrics (loudness, sharpness, fluctuation strength, roughness, and tonality) of different types of aircraft during landing and take-off using boxplots and linear regression. A non-parametric hypothesis test was employed to determine whether the same set of metrics showed statistically significant differences in sound samples from faulty and non-faulty gearmotors (Martínez and Soriano, 2020). A similar procedure was performed for Aures tonality and sharpness in aircraft engine variants (Torija *et al.*, 2019).

Therefore, the behavior of the metrics loudness, sharpness, fluctuation strength, roughness, Aures tonality, and prominence ratio, calculated from sound samples of electric motors, was analyzed using descriptive statistics, boxplots, and hypothesis tests in this work. A total of 213 motors covering the four considered operating conditions were selected from a manufacturer. For each motor condition analyzed, a sample with a specific number of motors was composed. As representative samples from the populations of electric motor operating conditions were examined, hypothesis tests assisted in generalizing the conclusions regarding the metrics for these populations, similar to the approach taken by Ganesan *et al.* (2021) for populations of three different motorcycle helmet brands.

2. METHODS

In this section, the manufacturing faults of electric motors investigated in this research will be described, as well as the procedures used in the acquisition and processing of sound signals. Finally, the methods and models selected to calculate the sound quality metrics will be presented.

2.1 Manufacturing Faults in Single-Phase Electric Induction Motors

This study analyzed single-phase induction electric motors used in washing machines. The motors have nominal power, voltage, and frequency of 1/4 hp, 127 V, and 60 Hz, respectively. A diagram illustrating the main parts of the analyzed motor type is presented in Figure 1. The investigated faults originated from the manufacturing process and are located in the bearing and two components in the stator: the lacing cord of its coils and the bracing tape (Figure 1). The occurrence of faults in the bearing is attributed to incorrect assembly procedures, which generate misalignment and overload in this component as well as mechanical vibration from other motor elements. Similarly, during stator assembly, operators inappropriately allow excess ends to emerge from the lacing cord and bracing tape. These protruding ends collide with rotor parts, causing undesired noises that characterize the faults in these components.
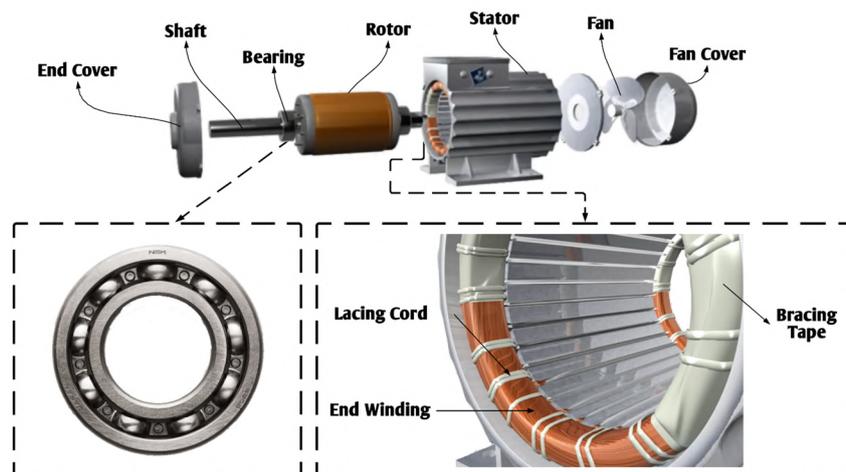

Figure 1. Diagram of the main components of an induction motor and the parts where the analyzed failures occur in this study.

At the end of a test station, operators are able to distinguish the noises generated by motors with these faults from those produced by motors in good condition through auditory inspection. The operators' experience with the sound characteristics of these products is used to decide whether to accept or reject them. For simplification in subsequent analyses, the investigated conditions will be abbreviated as BF for bearing faults, LCF for lacing cord faults, BTF for bracing tape faults, and FM for flawless motor.

2.2 Acquisition of Sound Signals from Electric Motors

From a total of 213 electric motors selected from a manufacturer, covering the four considered operating conditions, four samples were composed, representing each condition. The numbers of motors in the samples were: 14 for BF, 30 for LCF, 21 for BTF, and 148 for FM. The difference in size between the FM group and the fault groups was caused by the higher availability of non-defective motors at the end of the test station during the research period. The same reason accounts for the varying sizes of the fault groups. Trained operators performed the identification of the group to which each motor belonged through visual inspection of the components of these products at the end of the test line.

Before each motor's noise was recorded, they classified those that exhibited the characteristics of a specific fault into its representative group. Motors that were defect-free were classified in the FM group. The Siemens Simcenter Anovis system for end-of-line testing using acoustic and vibration signals is implemented at the manufacturer and was utilized for recording sound samples of the motors. This system includes two test cabins with acoustically treated internal walls, a PCB ICP 130F20 microphone, and a MeTool KS03 accelerometer, installed and calibrated in each cabin for capturing the acoustic and vibration signals. These sensors were connected to a signal acquisition device linked to a computer with signal analysis software. Figure 2 illustrates the interior of one of the cabins and the configuration of the experimental setup within it.
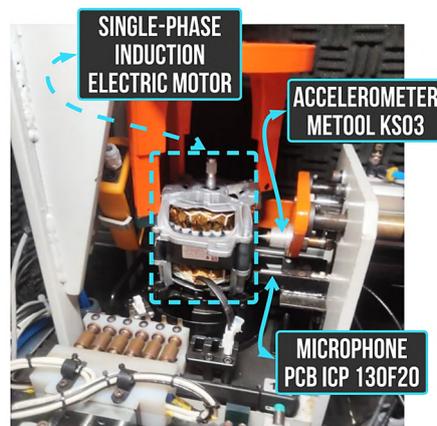

Figure 2. The interior of the cabin used for recording the sound samples of the electric motors.

Typically, sound quality metrics are obtained and analyzed from binaural recordings in anechoic chambers. However, the limitations imposed by the manufacturer regarding the removal of motors for recordings in external environments made this condition impossible. Recent studies (Kane and Andhare, 2019; Martínez and Soriano, 2020; Murovec *et al.*, 2020) have successfully analyzed faults in rotating machines and its components using these metrics from monaural recordings, without the use of a head and torso simulator (HATS). Moreover, Murovec *et al.* (2020) demonstrated the feasibility of using microphones in the very near-field condition to improve the signal-to-noise ratio (SNR) in the evaluation of the metrics, based on the work of Prezelj *et al.* (2013). Therefore, in this study, the microphones were positioned in very near-field to improve the SNR at the end of the test station, at 3 cm from the end windings of each motor recorded. The 213 electric motors were recorded at nominal voltage and frequency (127 V and 60 Hz), under no load conditions. The rotational speed of the motors under these conditions is around 1,800 RPM (30 Hz).

The signal analysis software stored the sensitivity data of the calibrated microphones and other necessary parameters for obtaining the sound pressure signals over time. The sound samples underwent preprocessing to ensure that only the relevant signal was present and to remove motor acceleration and deceleration ramps. This procedure was performed using MATLAB routines. Thus, at the end of this step, 213 time-domain sound pressure signals with a duration of 3 seconds were available for the calculation of sound quality metrics, corresponding to the measurement of each motor. Additionally, a sampling frequency of 51,200 Hz was used for all measurements.

2.3 Calculation of Sound Quality Metrics

The sound quality metrics loudness, sharpness, fluctuation strength, roughness, Aures tonality, and prominence ratio (PR) were calculated from the sound pressure signals of the motors. Loudness is a psychoacoustic measure that evaluates the subjective sensation of sound intensity or volume. Sharpness measures the perceived effect of an unbalance in the spectrum caused by increased high-frequency content in it. Fluctuation strength and roughness describe sensations associated with the presence of amplitude and frequency modulations in a sound. The first metric concerns modulations up to 20 Hz, while the second is associated with modulations between 20 and 300 Hz. Aures tonality and prominence ratio (PR) are related to the sensations caused by discrete components in sounds. In this study, loudness was obtained according to ISO 532-1 (ISO, 2017), which is based on the Zwicker model (Zwicker and Fastl, 2007).

The calculation of sharpness was performed following DIN 45692 (DIN, 2009). Fluctuation strength and roughness were calculated based on Zwicker models (Zwicker and Fastl, 2007) while Aures tonality on the model proposed in Aures (1985). The procedures described in the ECMA-74 standard (ECMA, 2012) were followed to obtain the prominence ratio (PR). Table 1 summarizes each of the standards or models proposed in the calculation of the metrics evaluated in this research.

Table 1. Standard or model selected for the calculation of each sound quality metric.

Sound Quality Metrics	Standard or Proposed Model
Loudness	ISO 532-1 (ISO, 2017)
Sharpness	DIN 45692 (DIN, 2009)
Fluctuation Strength	Zwicker's Model (Zwicker and Fastl, 2007)
Roughness	Zwicker's Model (Zwicker and Fastl, 2007)
Aures Tonality	Aures Model (Aures, 1985)
Prominence Ratio (PR)	ECMA-74 (ECMA, 2012)

Loudness, sharpness, fluctuation strength, and roughness were calculated using functions available in the MATLAB Audio Toolbox dedicated to this task. Based on the recommendations, data, and test signals provided by the ISO 532-1 (ISO, 2017) and DIN 45692 (DIN, 2009) standards, the loudness and sharpness algorithms implemented in MATLAB had their validation confirmed. As fluctuation strength and roughness do not have a standardized validation method, a procedure was adopted that involved the calculation of these metrics for signals provided in Zwicker and Fastl (2007) using MATLAB algorithms and the subsequent comparison of the results obtained with the values available in that same reference. The signals were provided in the .wav format along with a 1 kHz and 70 dB calibration signal.

Aures tonality and prominence ratio (PR) were obtained with the commercial software Siemens Simcenter Testlab 2019.1. Regarding the sound field selected for the calculation of the metrics, the free-field condition was considered because it is the closest to the interior of the test cabins, due to the application of the acoustic coating for sound absorption on all its walls. Both overall and specific results in Bark bands were obtained for most metrics. For some of them, spectrograms with frequency in psychoacoustic scale (Bark) were also generated.

3. RESULTS AND DISCUSSION

3.1 Normality of Sound Quality Metrics for Motor Conditions

For each analyzed condition of the electric motor, a sample with a specific number of motors was collected. The overall quantities of sound quality metrics were calculated for each motor in the sample. An analysis was conducted to assess whether the sample for each condition came from a normally distributed population for the evaluated set of metrics. Performing this step is crucial in identifying which hypothesis tests can be applied to determine if the observed differences in the overall metrics results between conditions are statistically significant or due to random sampling variability. Two methods were considered: probability plot analysis and the Anderson-Darling hypothesis test. Using both procedures aimed to increase confidence in the conclusions regarding normality, especially for samples with a small number of motors collected (<30). Montgomery and Runger (2007) emphasize that in such cases, deviations from linearity in probability plots can occur even in normally distributed populations.

The Anderson-Darling test allows examining the null hypothesis that the sample comes from a population with a normal distribution for the metrics against the alternative hypothesis that it does not, at a predetermined significance level. A significance level (α) of 0.05 was adopted for this test in all cases. Table 2 presents the p-value results of the test for evaluating the normal distribution of each condition concerning the overall values of sound quality metrics.

Table 2. Anderson-Darling test p-values and conclusions regarding the null hypothesis for each electric motor condition in relation to the overall quantities of the sound quality metrics ($\alpha = 0.05$).

Sound Quality Metric	Bearing (BF)	Lacing Cord (LCF)	Bracing Tape (BTF)	Flawless Motor (FM)
Loudness	0.378	0.024 (Reject)	0.654	0.019 (Reject)
Sharpness	0.017 (Reject)	0.019 (Reject)	0.685	0.871
Fluctuation Strength	< 0.001 (Reject)	< 0.001 (Reject)	0.242	< 0.001 (Reject)
Roughness	0.020 (Reject)	< 0.001 (Reject)	< 0.001 (Reject)	< 0.001 (Reject)
Aures Tonality	< 0.001 (Reject)	0.047 (Reject)	0.085	< 0.001 (Reject)

The test results show that, initially, normality for loudness should be rejected in the LCF and FM conditions at the pre-established significance level.

However, the probability plots associated with this metric in Figure 3 demonstrate that most of the FM data is found around the line. In addition, a p-value not so far from 0.05 is observed. Therefore, it was assumed that the normality for loudness is only rejected in LCF. The probability plots for sharpness (Figure 3) indicate that it is reasonable to adopt the conclusions obtained from the test for all groups. Therefore, normality was rejected for BF and LCF conditions.
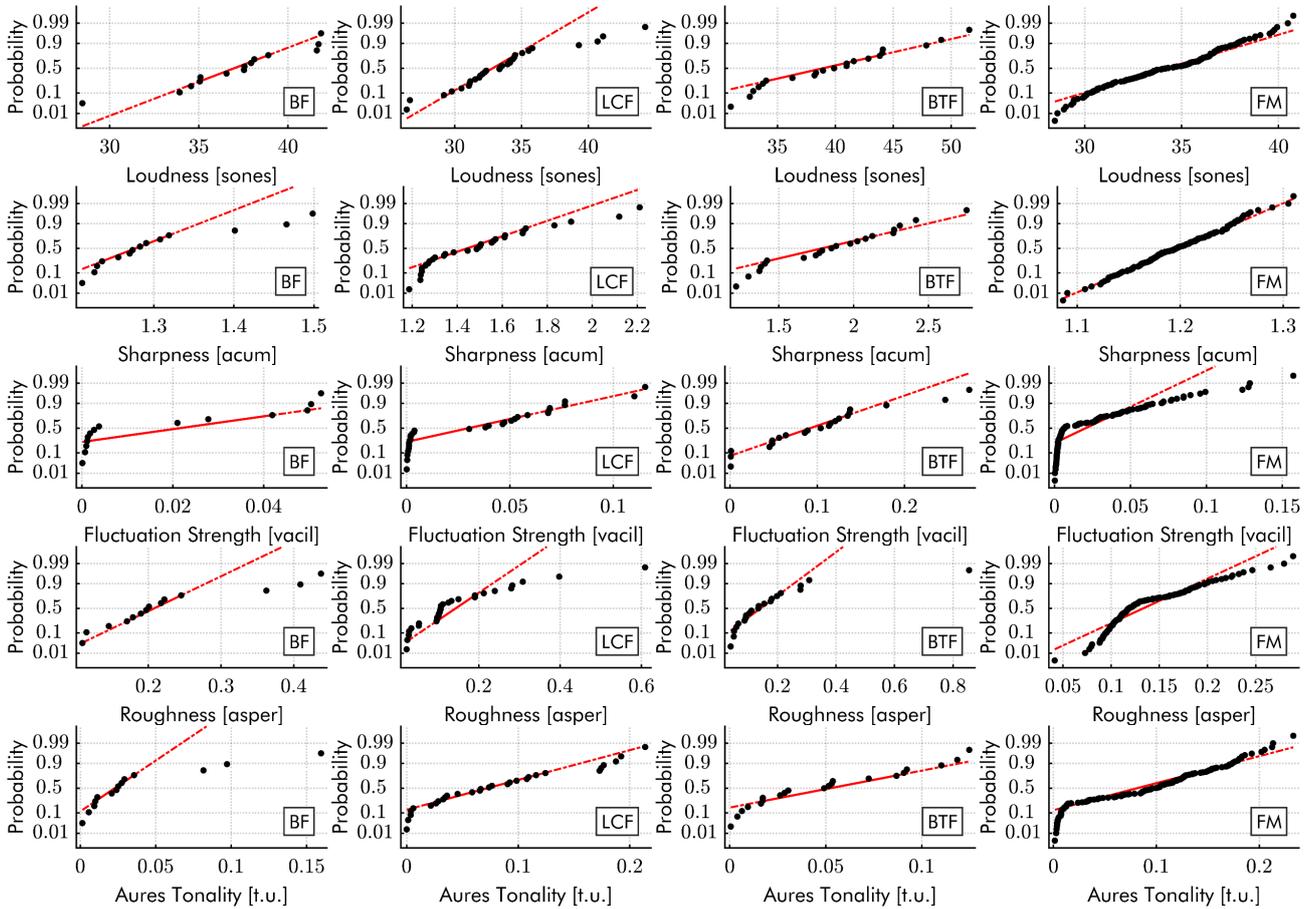

Figure 3. Probability plots of the sound quality metrics for each analyzed electric motor condition.

For the remaining metrics, in most of the conditions where the normality hypothesis was rejected, the probability plots show significant deviations from linearity, confirming the plausibility of the test results. In some cases, such as roughness in BF and BTF, and Aures tonality in BF and LCF, some linearity is observed in part of the data. However, the low p-value and significant deviations from the line exhibited by the rest of the data limit disregarding any inference from the test for these metrics. Table 3 summarizes the conclusions considered reasonable and adopted in this research regarding the probability distribution of the populations of each condition for the set of metrics. It is worth noting that the cells filled with "Normal" indicate that there is no statistically significant evidence to suggest that the analyzed sample comes from a non-normal population for the metrics, and thus the test fails to reject the null hypothesis at a significance level of 0.05.

Table 3. Conclusions adopted regarding the probability distribution of the populations for each electric motor condition concerning the overall values of sound quality metrics.

Sound Quality Metric	Bearing (BF)	Lacing Cord (LCF)	Bracing Tape (BTF)	Flawless Motor (FM)
Loudness	Normal	Non Normal	Normal	Normal
Sharpness	Non Normal	Non Normal	Normal	Normal
Fluctuation Strength	Non Normal	Non Normal	Normal	Non Normal
Roughness	Non Normal	Non Normal	Non Normal	Non Normal
Aures Tonality	Non Normal	Non Normal	Normal	Non Normal

3.2 Evaluation of Overall Results of Sound Quality Metrics

The overall values of sound quality metrics were obtained for each motor in the representative sample of each condition. Table 4 presents the averages of these results for each sample, while Figure 4 displays average prominence ratio spectrograms. Statistics that evaluate variability have not been inserted into Table 4 and are displayed later. The results show that the average behavior of the metrics is distinct in each condition. On average, the BTF sample has more intense loudness and sharpness content. The collision of the protruding ends of the tape with parts of the rotor, generating high-frequency pulsations, may explain the occurrence of a louder and more concentrated noise with high-frequency content. These metrics become potential candidates for characterizing this condition.

A lower average content of sharpness is found in FM. This result indicates that the presence of any of the motor faults causes an unbalance in the spectrum towards the high-frequency content. In addition, FM noises will tend to produce less discomfort than the others, since high values of this metric can cause shrill sounds to listeners (Fastl, 2005). This condition also stands out for having higher magnitudes of tonality metrics (Aures tonality and prominence ratio), followed by LCF. Figure 4 shows a more intense range of prominence ratio in FM and LCF compared to the other conditions, specifically located between 1.6 and 1.7 kHz, indicating the possibility of perceiving a tonal component in this region. The occurrence of discrete tones in this area is likely due to aerodynamic noise generated by the passage of motor fins. However, in general, the results of the tonality metrics were not as significant, and therefore, this perception may not be as evident for the noises of the specific type of electric motor in this study.

Table 4. Average overall magnitudes of the sound quality metrics for each condition of the electric motor.

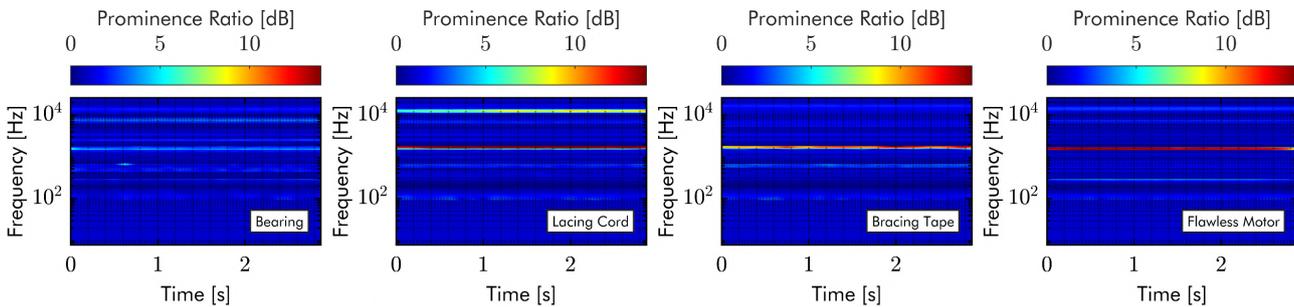| Group	Loudness [sones]	Sharpness [acum]	Fluctuation Strength [vacil]	Roughness [asper]	Aures Tonality [t.u.]
Bearing (BF)	37.06	1.30	0.02	0.23	0.04
Lacing Cord (LCF)	33.52	1.50	0.03	0.15	0.08
Bracing Tape (BTF)	39.82	1.86	0.10	0.17	0.05
Flawless Motor (FM)	34.22	1.20	0.02	0.13	0.09

Figure 4. Average prominence ratio spectrograms for each condition of the electric motor under analysis.

The BF condition exhibits a noticeably higher average roughness magnitude compared to FM. Mian *et al*. (2022) demonstrated that the combination of the main faults in the bearing of induction motors results in higher roughness compared to the non-defective condition. In the LCF condition, intermediate quantities were observed for most of the metrics. Therefore, using these metrics in combination is recommended for a concise characterization of this group. Fluctuation strength showed low magnitudes across all groups, indicating that slow fluctuations in amplitude or frequency are not present intensively or have a modulation frequency distant from the one that maximizes this metric (4 Hz).

The variability of the metrics in each condition was analyzed using boxplots (Figure 5) and interquartile ranges (Table 5) obtained from their global results. The boxplots also allow for the comparison of medians, the observation of data distribution behavior, and the identification of outliers. It is easily observed from the boxplots that the distribution of the metrics is asymmetric in several cases, which corroborates part of the conclusions from the Anderson-Darling test and the behaviors observed in the probability plots. These results indicate that the metrics do not follow a normal distribution under most conditions, making it reasonable to consider the occurrence of non-symmetric distributions. Lower variability was found for sharpness in FM, while the opposite was observed in BTF. The latter group exhibited higher variability in most metrics, particularly in loudness and sharpness, indicating that the generation of faults in this group has a more random behavior.

Although the mean values of loudness and sharpness distinguish this condition well, the high variability found in it will limit the isolated use of these metrics to concisely characterize it in classification methods. Additionally, in future listening tests with selected sounds from BTF, it is expected that the quantification of listeners' perceptions regarding the sensations of sound intensity and sharpness or other attributes related to these metrics may also show greater dispersion, opposite to the case of perceptual characteristics associated with the sharpness metric in FM. In roughness, a larger number

of outliers is observed in the conditions, always with higher values, which may indicate anything from simple random variations to greater sensitivity of the model used in this metric, thus raising the need for more detailed investigations.

When considering the order of magnitude of the mean global results of the metrics and the interquartile ranges, it can be noted that, overall, higher variability occurs in fluctuation strength and Aures tonality. The previous results showed that the global values of the first metric do not characterize the conditions well due to low magnitudes, so the high dispersion is not a concern in this case. However, for Aures tonality, careful analyses should be performed when using this metric to successfully characterize the conditions.
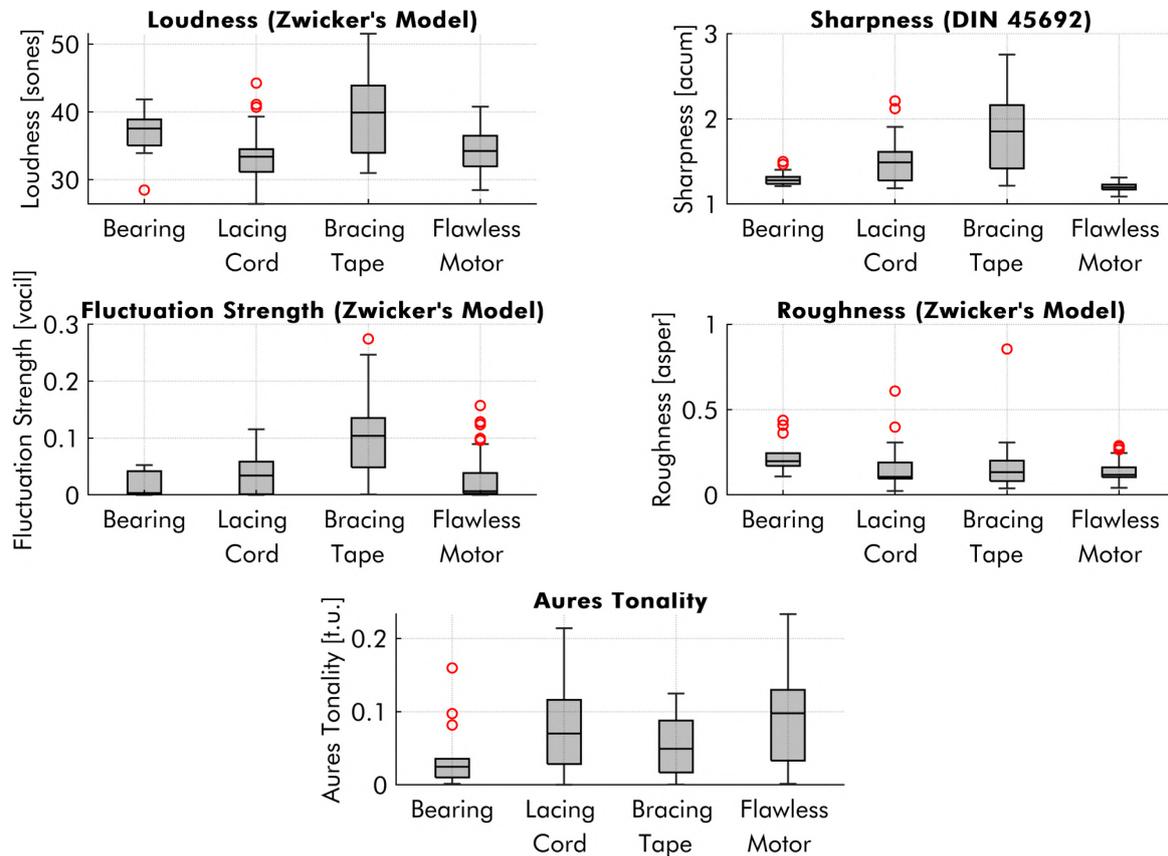

Figure 5. Boxplots of the overall values of sound quality metrics for each condition of the electric motor.

Table 5. Interquartile ranges of the overall results of sound quality metrics for each condition of the electric motor.

Group	Loudness [sones]	Sharpness [acum]	Fluctuation Strength [vacil]	Roughness [asper]	Aures Tonality [t.u.]
Bearing (BF)	3.84	0.08	0.04	0.07	0.03
Lacing Cord (LCF)	3.35	0.34	0.06	0.09	0.09
Bracing Tape (BTF)	9.93	0.74	0.09	0.12	0.07
Flawless Motor (FM)	4.52	0.06	0.04	0.06	0.10

Since all the overall results of the metrics presented so far were collected from samples originating from representative populations of each condition, a hypothesis test was performed to assess whether the differences observed in these results are statistically significant among these populations. The conclusions obtained previously and presented in Table 3 regarding the normality of the groups considered that most of them do not follow a normal distribution. Therefore, parametric tests are not recommended, which motivated the application of the non-parametric Wilcoxon rank-sum test.

The assumption of independence between observations within each condition and between conditions is satisfied, as well as the assumption of random sampling. In this study, the application of the test did not directly compare the medians of the populations but rather allowed for verifying if there are statistically significant differences between the groups regarding the overall mean results of the metrics.

The null hypothesis of the test is that the results do not differ significantly, while the alternative hypothesis is that they do differ. A significance level of 0.05 was adopted. The analyses conducted involved comparing the FM condition with the other conditions for each metric, as the main interest lies in assessing the plausibility of the metrics being able to

distinctively characterize the fault-free condition from those with any type of fault. Table 6 presents the obtained p-values and the conclusions regarding the null hypothesis for each comparison. In general, for each metric, it is reasonable to consider that in at least one of the comparisons there are statistically significant differences. This result allows for generalizing the comparisons from the samples to the populations of motors in each condition and highlights the potential of the evaluated sound quality metrics as useful features in automated methods for diagnosing manufacturing faults in the electric motors under study.

Table 6. Wilcoxon rank-sum test p-values and conclusions regarding the null hypothesis ($\alpha = 0.05$).

SQ Metric	Bearing (BF)	Lacing Cord (LCF)	Bracing Tape (BTF)
Loudness	0.002 (Reject)	0.126	< 0.001 (Reject)
Sharpness	< 0.001 (Reject)	< 0.001 (Reject)	< 0.001 (Reject)
Fluctuation Strength	0.159	0.869	< 0.001 (Reject)
Roughness	< 0.001 (Reject)	0.274	0.896
Aures Tonality	0.003 (Reject)	0.313	0.005 (Reject)

3.3 Evaluation of Specific Quantities of Sound Quality Metrics

In addition to the overall quantities, specific values on the Bark scale were also obtained. Figure 6 shows the average results of each metric for the samples in the analyzed groups. The specific results help in understanding what was observed with the global values. The BTF exhibits the highest overall average magnitudes of loudness, sharpness, and fluctuation strength due to the considerable increase in the specific quantities of these metrics in the range between 16 and 24 Bark (3,152 and 16,632 Hz). The lower specific sharpness quantity in FM at the same location is also responsible for the lower average global value found in this condition. As the weighting function of the applied sharpness model increases from 16 Bark, the effect of weighting is smaller in this condition. The greater discrepancy in specific loudness and sharpness between the conditions is also more evident in this range.

All conditions show higher specific loudness in the 0 to 2 Bark region (0 to 204 Hz), indicating a low-frequency content present in the noise of electric motors across all groups. An elevation in loudness in the 10 to 12 Bark region (1,255 to 1,692 Hz) is also observed in FM, which is associated with the highest mean value of Aures tonality among the groups and the most intense region in the prominence ratio spectrogram. For fluctuation strength, the behavior of the groups is similar across the scale Bark, except for the BTF and, in the upper bands, for LCF. The highest overall mean result of roughness for BF can also be confirmed through specific values. This condition has more prominent levels of roughness starting at 8 Bark (922 Hz).
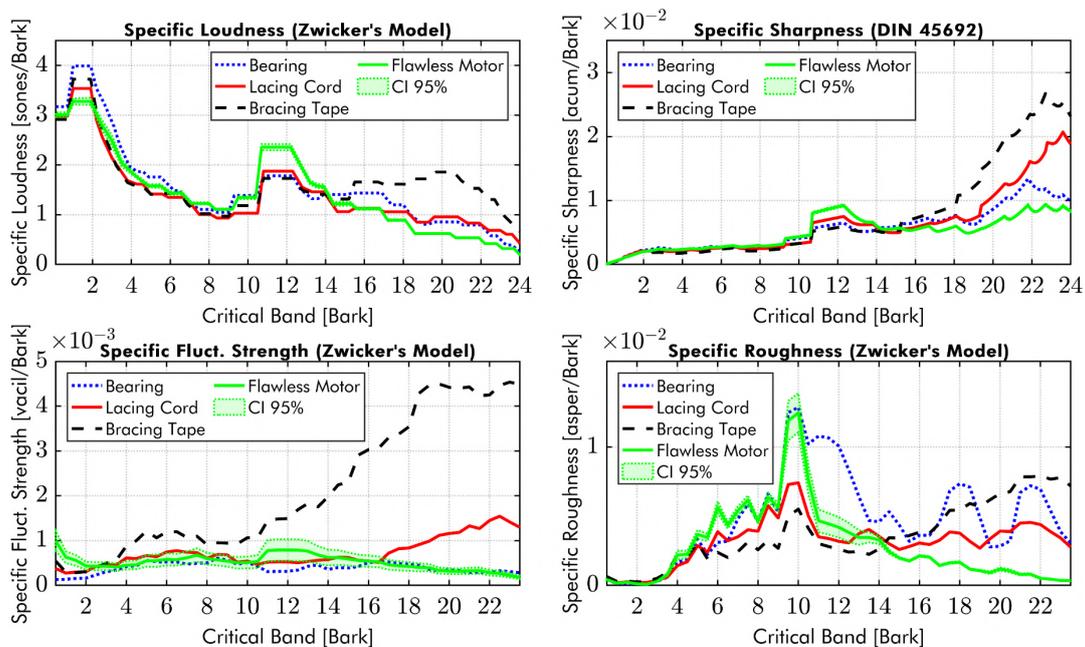

Figure 6. Average specific values of sound quality metrics for each analyzed condition of the electric motor and confidence intervals of the mean for each metric in the FM condition.

A visual analysis of the specific mean values of sharpness, fluctuation strength, and roughness using psychoacoustic spectrograms is presented in Figure 7. The same results observed in Figure 6 are evident in these spectrograms. As the noise of the investigated electric motors has a stationary character, significant changes do not occur over time. Therefore, these visual representations are provided solely for easier and quicker identification of the distinct behaviors of the specific quantities for the three metrics.

It is noticeable a higher specific sharpness and fluctuation strength content between 16 and 24 Bark (3,152 and 16,632 Hz) in BTF, as well as the distinct behavior of specific roughness among the conditions. This metric is more prominent in a range between 8 and 12 Bark (915 and 1,720 Hz) for BF and FM and spreads to other regions of the spectrum in the first condition. The peculiarities found in the spectrogram results can be further explored through computer vision techniques for application in classification procedures of the analyzed conditions.
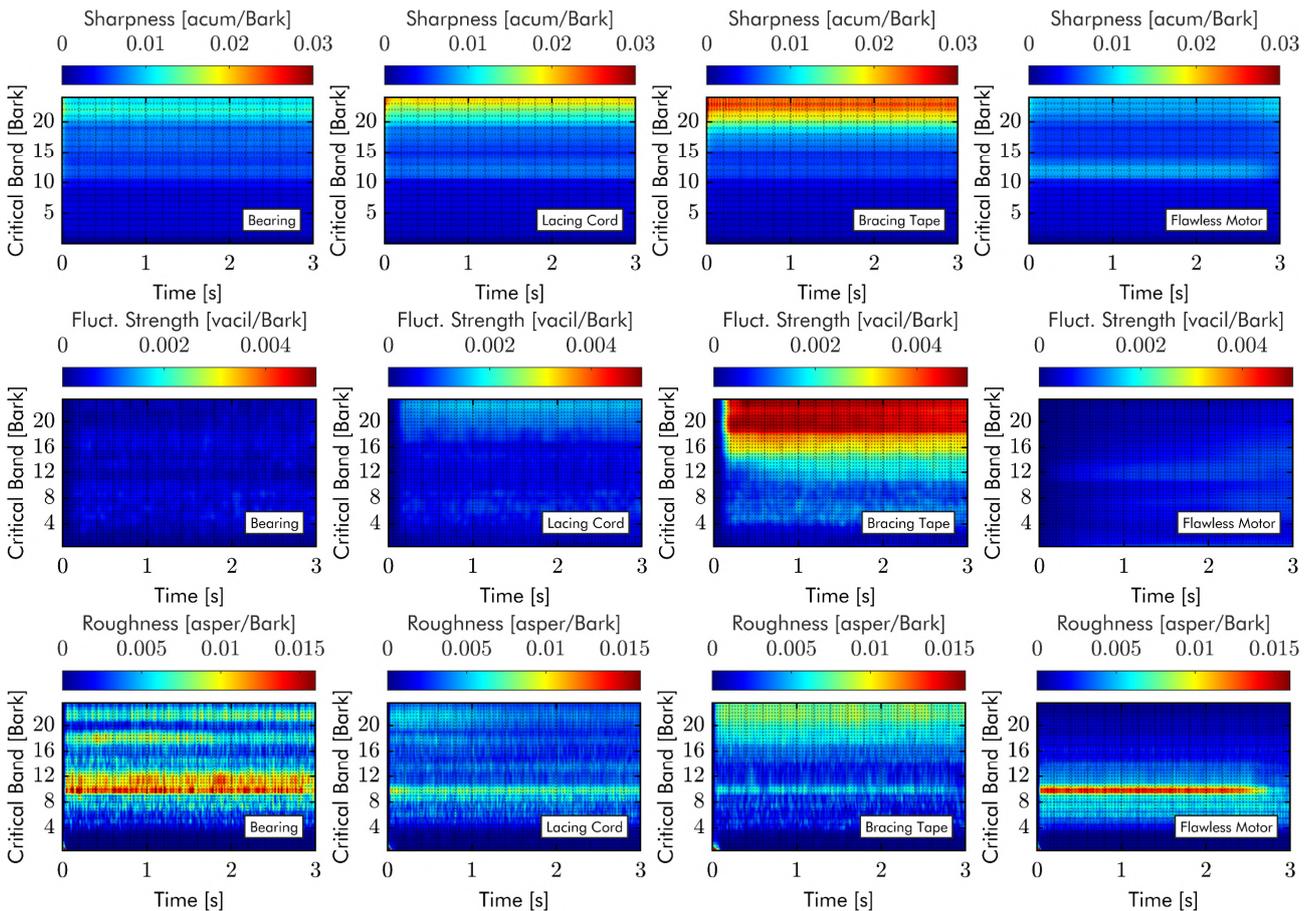

Figure 7. Average spectrograms of specific sharpness, fluctuation strength, and roughness for each analyzed condition.

4. CONCLUSIONS

This research analyzed the behavior of sound quality metrics for four different operating conditions of single-phase induction electric motors. Normality tests were conducted to verify if the populations of each condition follow a normal distribution. Normality was rejected in most of the analyses, necessitating the application of non-parametric hypothesis tests to verify if the differences found in the metrics results are statistically significant or due to sampling randomness.

The overall results of the metrics demonstrated that their average behavior is distinct for each condition. Some conditions stood out for presenting higher intensity in certain metrics, indicating specific characteristics in the noises produced by the motors in each case. The variability of the metrics was analyzed, and greater dispersion was found in the BTF condition, particularly in loudness and sharpness. Overall, fluctuation strength and Aures tonality exhibited the highest variability. The non-parametric Wilcoxon rank-sum test showed statistically significant differences between the populations of each condition to the overall results of the metrics, allowing for generalizing the conclusions obtained from the samples. The specific quantities in the critical bands contributed to the understanding of the global behavior of the metrics in each case.

Thus, this work demonstrated that the analyzed sound quality metrics can be effective in characterizing and differentiating the investigated conditions based on the noises produced by the electric motors, with the potential to be used in automated methods for diagnosing manufacturing faults in these products, contributing to the efficiency and

reliability of these processes. Additionally, the study of the metrics' behavior suggested which of them are more likely to correlate with attributes that can be perceived in the noises of the examined conditions in future listening tests.

5. ACKNOWLEDGEMENTS

6. REFERENCES

Aures, W., 1985. "A procedure for calculating sensory pleasantness of various sounds (in German)". *Acustica*, Vol. 59(2), pp. 130-141.

DIN, 2009. *DIN 45692:2009, Measurement technique for the simulation of the auditory sensation of sharpness*. Deutsches Institut für Normung DIN. Berlin, Germany.

ECMA, 2012. *ECMA-74:2012, Measurement of airborne noise emitted by information technology and telecommunications equipment*. ECMA International. Geneva, Switzerland.

Fastl, H., 2005. "Psycho-acoustics and sound quality". In *Communication acoustics*. Springer, Berlin, pp. 139-162.

Ganesan, K., Bienert, J. and Zhao, X., 2021. "Psychoacoustic assessment of noise under a motorcycle helmet". In *Proceedings of the 47th Annual Conference on Acoustics - DAGA 2021* (in German). Vienna, Austria.

ISO, 2017. *ISO 532-1:2017, Methods for calculating loudness - Part 1: Zwicker method*. International Organization for Standardization ISO. Geneva, Switzerland.

Kane, P.V. and Andhare, A.B., 2019. "End of the assembly line gearbox fault inspection using artificial neural network and support vector machines". *International Journal of Acoustics and Vibration*, Vol. 24(1), pp. 68-84.

Martínez, P.P. and Soriano, J.R., 2020. "A comparison between psychoacoustic parameters and condition indicators for machinery fault diagnosis using vibration signals". *Applied Acoustics*, Vol. 166.

Mian, T., Choudhary, A. and Fatima, S., 2022. "An efficient diagnosis approach for bearing faults using sound quality metrics". *Applied Acoustics*, Vol. 195.

Montgomery, D.C. and Runger, G.C., 2007. *Applied statistics and probability for engineers*. 4rd Edition. John Wiley & Sons.

Murovec, J., Čurović, L., Novaković, T. and Prezelj, J., 2020. "Psychoacoustic approach for cavitation detection in centrifugal pumps". *Applied Acoustics*, Vol. 165.

Prezelj, J., Lipar, P., Belšak, A. and Čudina, M., 2013. "On acoustic very near field measurements". *Mechanical Systems and Signal Processing*, Vol. 40(1), pp.194-207.

Torija, A.J., Roberts, S., Woodward, R., Flindell, I.H., McKenzie, A.R. and Self, R.H., 2019. "On the assessment of subjective response to tonal content of contemporary aircraft noise". *Applied Acoustics*, Vol. 146.

Vieira, A., Mehmood, U., Merino-Martínez, R., Snellen, M. and Simons, D.G., 2019. Variability of sound quality metrics for different aircraft types during landing and take-off. In *25th AIAA/CEAS Aeroacoustics Conference*. Delft, The Netherlands.

Zwicker, E. and Fastl, H., 1999. *Psychoacoustics: Facts and Models*. 2rd Edition, Springer-Verlag, Berlin.

Zwicker, E. and Fastl, H., 2007. *Psychoacoustics: Facts and Models*. 3rd Edition, Springer, Heidelberg.

7. RESPONSIBILITY NOTICE