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ORIGINAL RESEARCH

Data sonification of film capacitors

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Abstract

Film capacitors are playing an increasingly important role in power-related fields, driven by the continuous development of dielectric materials and practical needs. Long-term accumulation has also led to an increasing wealth of data related to film capacitors. Sonification opens up a new way for people to make good use of data from film capacitors. A framework for sonifying film capacitors data based on TwoTone is presented. Based on the analysis and discussion, it is clear that the sonification results can easily represent the monotonic variation pattern of film capacitors data. What's more, the sonification results increase the possibility that people pay attention to the changing trend of film capacitors data when there is no significant difference in the visual perception of the data. In addition to providing a new way of music generation of electrical equipment, the method proposed is expected to contribute to theory reference in typical scenarios, such as factory calibration of film capacitors, monitoring of film capacitor operation status, and presentation of statistical data of film capacitors' dielectric materials, which will help us to better understand the distribution characteristics of polymer films.

KEYWORDS

capacitors, dielectric losses, dielectric materials, polymer films, power capacitors

1 | INTRODUCTION

Under the wave of green and clean energy, the use of renewable energy sources has received attention from industry and academia [1, 2]. In this process, energy devices for renewable energy applications have become key players. Therefore, many engineers and scholars have put a lot of effort into the technology and principles of energy devices. Among the many pearls of wisdom, film capacitors with excellent performance such as high reliability and long life are the ones that cannot be ignored [3, 4]. As people witness the continuous development of the film capacitor industry, a large amount of data on film capacitors has been recorded and compiled. To make good use of this resource and further unlock the data value of film capacitors [5], methods, such as highlighting features [6], mining implied relationships [7], and constructing data models [8] have been used. In these attempts, the visual presentation is the main mode of expression. The variety and complexity of issues involved in film capacitors [6, 9] require a more comprehensive perception of them from different perspectives. We can make full use of senses other than the eyes, such as the ears. Sonification has been shown to be promising in helping blind and visually impaired people access information through sound. For example, the experiment's state is transformed into sound so that the visually impaired students can judge the experiment's state and thus gain better knowledge about it [10, 11]. In the intersection of capacitors and sound, capacitive sensors, which reflect changes such as object motion through changes in capacitances [12, 13], can serve as an indication of position and help music learners to practice their instruments more precisely [14]. Or, make the capacitor directly part of a new type of electronic harmonic resonator with musical potential [15]. While capacitors are helping to develop the field of sound, some musical ideas will also inspire people in the capacitor industry. For example, the search algorithm built by simulating the musician to adjust the pitch of each instrument to achieve harmony has become a tool to cope with the layout of capacitors [16].

In view of this, TwoTone was used to sonify film capacitors data with different trends, and the sonification results were analysed. Finally, we discuss the possible directions for future improvement of data sonification of film capacitors.

2 | METHODS AND TOOLS

In order to present the data as sound to help people understand the complex information in the film capacitor data more effectively, we choose TwoTone to sonify the data of film capacitors. TwoTone is a Java-Script-based tool [17], which can map data to musical pitches online [18, 19]. Figure 1 shows the framework for data sonification of film capacitors using TwoTone. The imported film capacitor data is stored and calculated in the form of arrays. TwoTone converts the data set into MIDI (Musical Instrument Digital Interface) files according to the mapping rules. The latter could be changed into the corresponding audio track by the synthesiser. The A note above middle C is usually set at 440 Hz, which is often considered the 'standard pitch'. The logarithmic relationship between a number p and the fundamental frequency f can express the pitch of a tone [20]. According to the MIDI standard, the mathematical relationship between the fundamental frequency f and the corresponding number p can be described by the Equation (1) or Equation (2).

$$p = 69 + 12 \times \log_2\left(\frac{f}{440}\right) \tag{1}$$

$$f = 440 \times 2^{\frac{(p-69)}{12}} \tag{2}$$

where 12 is the size of octaves. 69 is the number assigned to the standard pitch. The data analyst can adjust parameters to affect the effect of the final audio track, and the parameters set in this paper are shown in Table 1. Here, different types of instruments, different track tempos, and different scale ranges could be tried to get more personalised settings, making the sonification results more 'acceptable' to people, thus enhancing the data 'absorption' effect.

TABLE 1 Set parameters.

Instrument	Piano	**Start octave**	Auto
Key	C(Major)	**Track tempo**	12×
Scale range	2 octaves	**Arpeggio**	Ascending

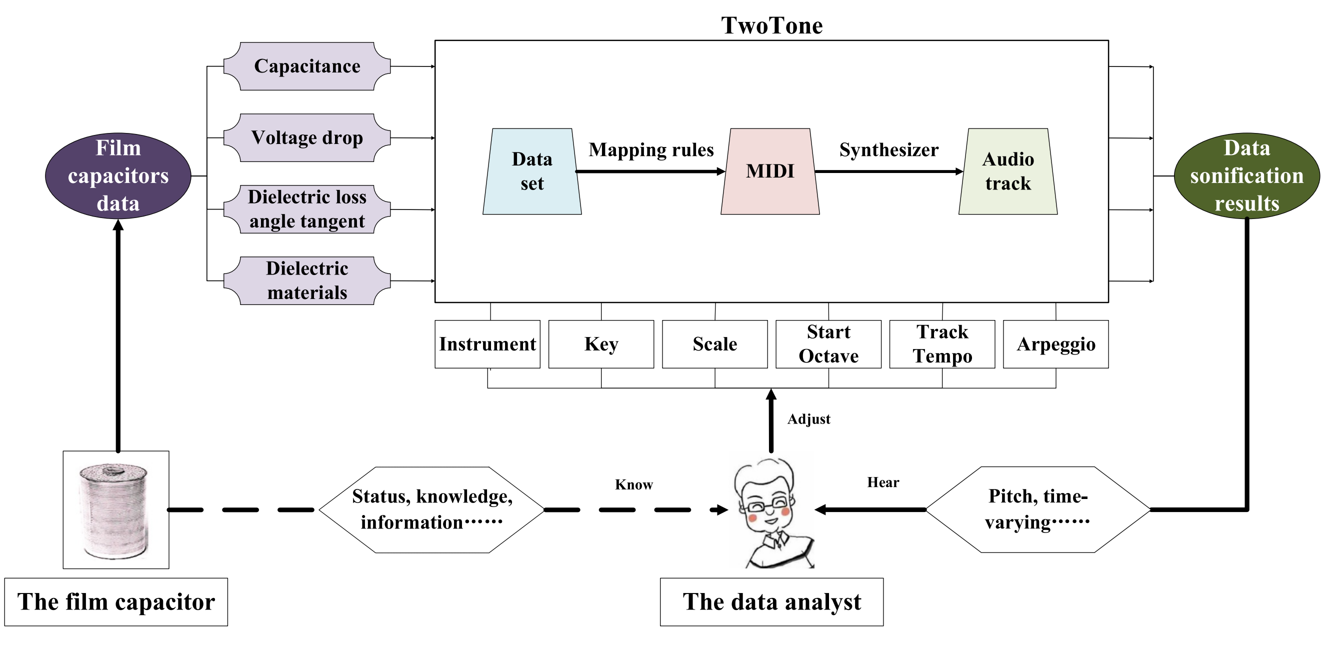

FIGURE 1 Framework for data sonification of film capacitors.

After obtaining the corresponding data sonification results of the film capacitors through the above method, further plot the audio waveform of the sonification results. Taking the audio conversion results in MP3 format in MATLAB environment as an example, the horizontal axis uses the actual duration of the audio conversion results (obtained by dividing the length of sampled data by the sample rate), and the vertical axis variable uses the average value of each channel to depict the waveform of the audio conversion results over time. The codes for the audio waveform of the data sonification results can be found in ref. [21].

3 | CASE STUDY

3.1 | Applications on different data types

Capacitance: Wrap a biaxially oriented polypropylene base film modified with high dielectric constant nanoparticles into a capacitor [8]. Place the film capacitor made of this new material in a room temperature and humidity environment, measure the capacitance of the film capacitor using an LCR metre at a fixed time every day, and record the data of the capacitance changing over time for 70 days. The capacitance data of the film capacitor is visualised and sonified by using the method introduced in Chapter 2. Figures 2a,b show the results of MATLAB-based data visualisation and TwoTone-based musical scale, respectively, and the sonification results can be found in the URL [22]. The similar shape of visualisation results Figure 2a and musical scale Figure 2b shows that the sonification results can accurately map the data variation pattern. The overall pattern of change in the capacitance data is consistent (downward trend), with local fluctuations. Its corresponding sonification results also give a downward trend. The sonification results will help professionals in the film capacitor industry understand the patterns of new equipment made from new materials in unfamiliar environments. On the basis of traditional visualisation results, the changes in pitch will allow operation and maintenance personnel to monitor capacitances with optimal cognitive resource space [23, 24], thereby having more opportunities to pay attention to changes in capacitances.

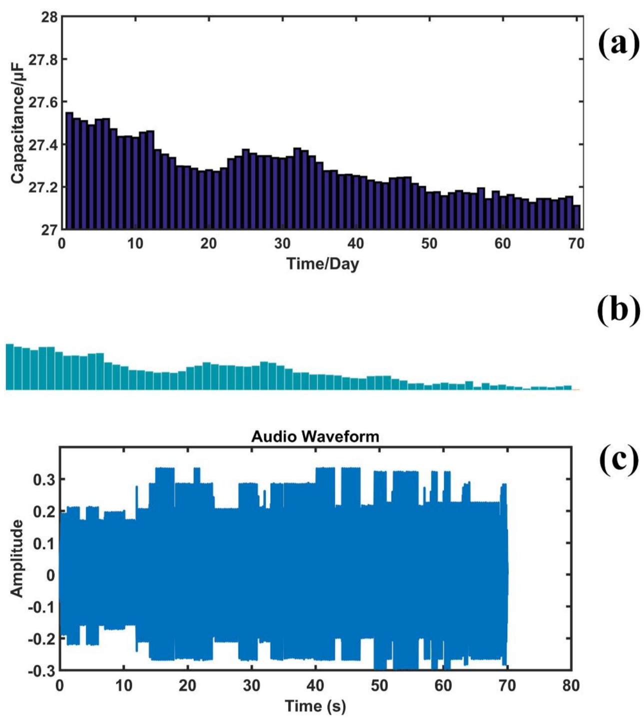

FIGURE 2 Capacitance. (a) Data visualisation results (b) The corresponding musical scale (c) The corresponding audio waveform.

Voltage drop: Charge a metallised film capacitor through a DC source until the voltage on it stabilises for more than 5 min. At this point, disconnect the charging circuit through the switch, and record the continuous drop in voltage on the metallised film capacitor as the number of days increases through an oscilloscope with a high-voltage probe [4]. The film capacitor voltage drop data is visualised and sonified by using the method introduced in Chapter 2, and sonification results can be found in the URL [25]. Sonification results with a monotonic descent pattern are more easily distinguished by the human ear. The decrease in the pitches of the sonification result corresponds to the voltage drop. However, when the subsequent numerical changes are not significant, it is also difficult to distinguish these subtle features based on these sonification results. This also inspires the subsequent design of data sonification. We could amplify it when data fluctuations are small so that listeners can capture subtle information and, at the same time, tell listeners by using different timbres that this is the amplified sonification result.

Dielectric loss angle tangent: Using the same object as the previous capacitance measurement [8] (the film capacitors made of the new film material), measurement environment, measurement time interval, and measurement equipment, measure and record the dielectric loss angle tangent data of the film capacitor from day 61 to day 70. The dielectric loss angle tangent data of the film capacitor is visualised and sonified, and sonification results can be found in the URL [26]. Compared with Figures 2–4 presents data visualisation results with insignificant visual differences. In cases where there is no significant visual difference, the sonification results increase the likelihood that people will notice changes in the film capacitor data so that immediate adjustments can be made to avoid hazards. Typical scenarios include power equipment dispatch rooms that require real-time online monitoring. Furthermore, for data with insignificant differences, more refined sonification methods can be tried later to improve the discrimination.

Absolute error: A single prediction model for the capacitances of the film capacitor was constructed based on the smoothing spline theory. Let the single prediction model extract patterns from the capacitance data in the first 60 days obtained from the previous capacitance measurement [8]. Reuse the extracted patterns to predict the capacitances for the next 10 days. By comparing the predicted values with the actual measured values, the absolute error data from the single prediction model is obtained. The absolute error data from the single prediction of the film capacitor is visualised and sonified

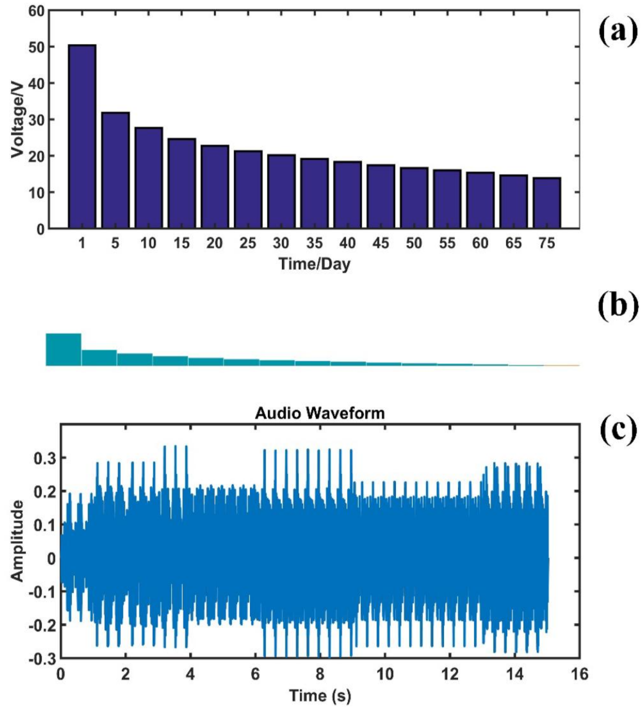

FIGURE 3 Voltage drop. (a) Data visualisation results (b) The corresponding musical scale (c) The corresponding audio waveform.

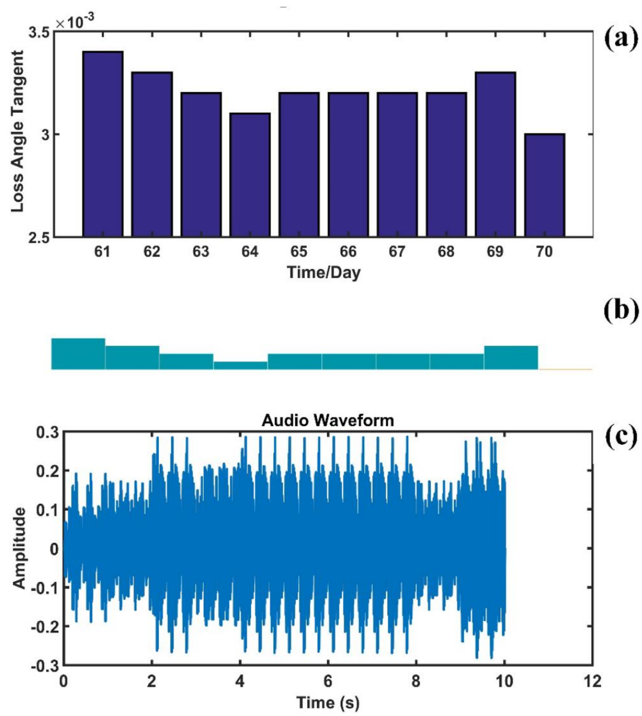

FIGURE 4 Dielectric loss angle tangent. (a) Data visualisation results (b) The corresponding musical scale (c) The corresponding audio waveform.

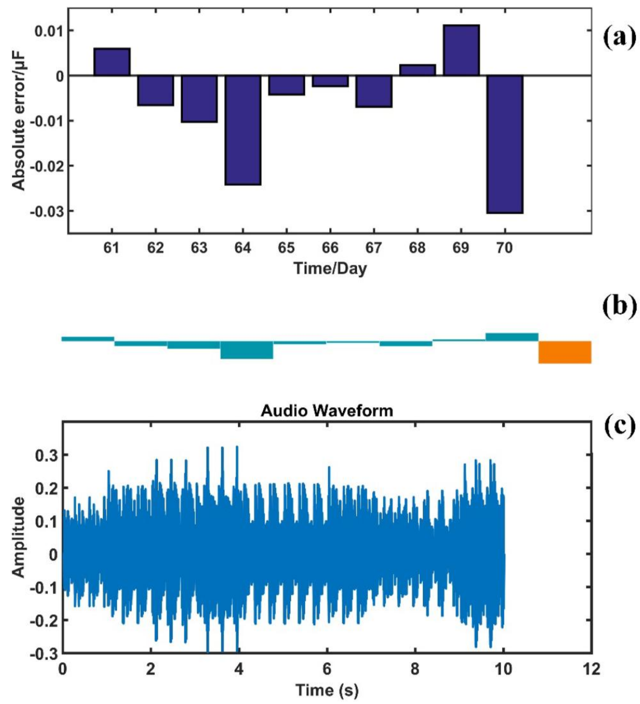

FIGURE 5 Absolute error. (a) Data visualisation results (b) The corresponding musical scale (c) The corresponding audio waveform.

like before, and sonification results can be found in the URL [27]. It can be seen from Figure 5 that for data with positive and negative values, the musical scale can also present this feature. The change from positive to negative values is also clearly perceptible in the sonification results. This is also a manifestation of the ability of sonification results to transmit more data information.

Distribution digits for film capacitors' dielectric material types: Data on 54,604 film capacitor products were collected through the Internet [7]. Label the dielectric film material used in each film capacitor and use a different number starting from 1 to identify each dielectric film material type. Then, the digits of film capacitor products corresponding to each dielectric film material type can be counted. The data of distribution digits for film capacitors' dielectric film material types is visualised and sonified, and sonification results can be found in the URL [28]. For the specific dielectric material corresponding to the code, please see the literature [7]. For data with significant abrupt changes, the sonification results allow one to better remember the abrupt data points and thus discover the overall distribution pattern of the data. However, there are cases where the current sonification results do not distinguish two data with little differences in values, such as the distribution digit of code 1 and the distribution digit of code 2. Although little differences between the two can be observed in the visualisation results. At the same time, it should be noted that there is a pleasing experimental result. In the perception of professional data with distributed characteristics, optimising the design scheme of sonification results can enable people with weak professional knowledge to achieve the same effect as those with deep professional knowledge [29]. This can provide an improvement direction for the sonification of more distribution data of film capacitors in the future.

3.2 | Audio waveform

By using the method introduced in Chapter 2, the audio waveforms of the sonification results of each film capacitor data can be obtained, as shown in Figure 2c–6c. As we can see, the specific pitches corresponding to specific values in the data of film capacitors are represented by specific patterns in audio waveforms. A typical example is that in Figure 4, the dielectric loss angle tangents from day 65 to day 68 are the same, and the amplitudes of the audio waveform corresponding to the time are also the same. When there is a significant gap between the data points before and after, the amplitudes of audio waveforms correspond to a gap. For example, in Figure 6, the 'drop' between the digits of capacitors corresponding to dielectric material number 14 and the digits of capacitors corresponding to neighbouring dielectric materials number 13 and 15 corresponds to a 'drop' in amplitudes of the audio waveform. These all indicate that the sonification results are indeed accurate in transmitting information in the data of film capacitors, and this effect is reflected in all the tested data. Of course, the losses and biases that exist during the process of converting data into sound [30] are also worth the attention of researchers who are committed to improving the effectiveness of data sonification in the future.

In addition, comparing the visualisation results in Figure 2–6 with the corresponding audio waveforms, it can be found that compared with the static data visualisation results, the continuous audio waveforms that can more directly reflect time are significantly more 'complex'. Utilising the inherent multidimensionality [31] of sound to enhance the ability for scientific discovery in complex datasets is one of the motivations behind many data sonification projects [32].

3.3 | Further attempt

Considering the distribution digits for film capacitors' dielectric material types as frequencies, Figure 7 can be got by using Equation (1). The variation characteristics of Figure 6 can be seen in Figure 7, so 'the variation characteristics of the data are an important factor in its transformation into sound' can be thought of. The variance of the normalised data is used to assess the degree of data volatility contained in various types of film capacitor data, and this metric S is then compared to the volumes of the corresponding data sonification results. For a data sequence containing n data points $\{x_1, x_2, \ldots, x_n\}$:

$$\begin{cases} x_i{}' = \dfrac{x_i}{\max\{|x_1|, |x_2|, \ldots, |x_i|, \ldots, |x_n|\}} \\ \overline{x_i{}'} = \dfrac{1}{n}\displaystyle\sum_{i=1}^{n} x_i{}' \\ S = \dfrac{1}{n}\displaystyle\sum_{i=1}^{n}\left(x_i{}' - \overline{x_i{}'}\right)^2 \end{cases} \tag{3}$$

Figure 8 does not present the expected positive, perfectly correlated relationship between S and volume, which is reminiscent of the correspondence between p and f shown in

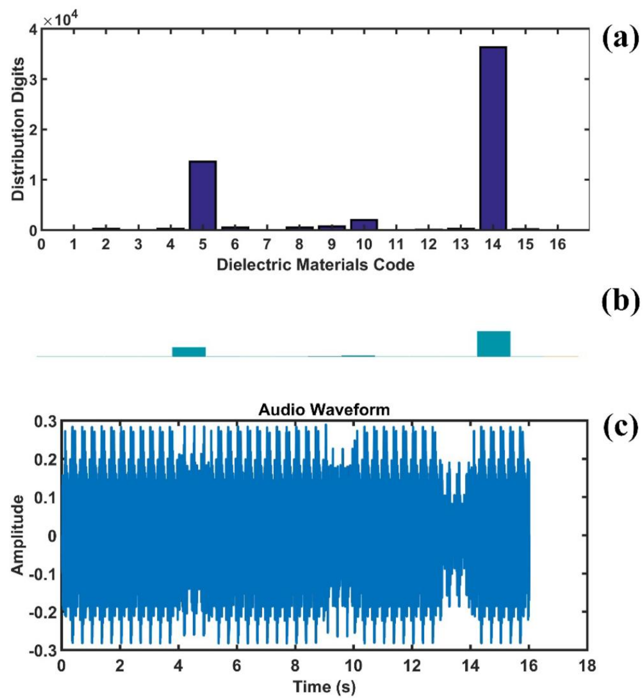

FIGURE 6 Distribution digits. (a) Data visualisation results (b) The corresponding musical scale (c) The corresponding audio waveform.

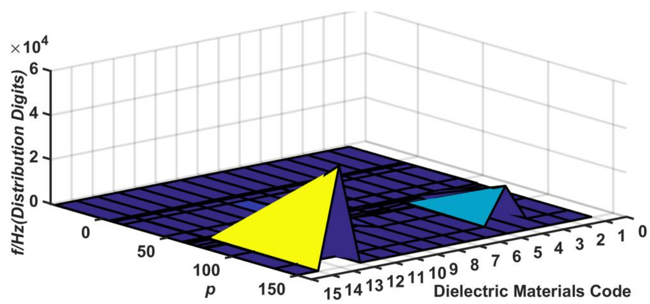

FIGURE 7 Distribution digits and corresponding number p of different materials.

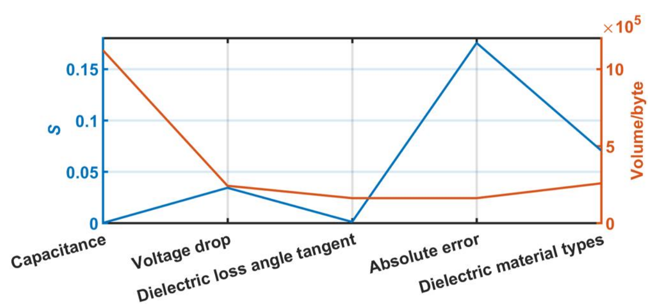

FIGURE 8 Different data types' S and corresponding sonification results' volumes.

Figure 7. The difference in the number of data points should also affect the volume of the final sonification results, which are to be further explored.

4 | DISCUSSIONS AND CONCLUSIONS

4.1 | Discussions

The relationship between the contributions of this paper and the dielectric material. As one of the most important dielectric application equipment, film capacitors, their performance enhancement and condition monitoring are related to the industrialisation of advanced energy storage dielectric materials [3] and the safe and stable operation of green power systems [1, 2]. The sonification method, the idea of analysing the sonification results, and the sonification framework proposed in this paper open up new technical paths for the understanding of the mechanism of novel film capacitors made of new materials in new environments. The new experiences gained from them can also help guide the targeted optimisation of dielectric materials [33]. Specifically, these lessons derived from the data sonification results can inform the AI-based design [34–36] of dielectric materials during model construction. In addition to the learned data itself, the models incorporate more specialised knowledge and perform better as a result [37].

The meaning of humans in the data sonification of film capacitors. We are moving towards a more advanced AI era. It is tempting to ask the question: if, for example, the production pipeline of film capacitors is all handed over to an AI agent, with no human involvement at all, to whom will the data sonification results be delivered? As described in the ref. [38], the mode of coexistence between humans and AI (agents) will remain the main theme of this transition until we formally enter the era of high dependence on AI. And this transition process can also transform the storage of human experience and knowledge into the AI agent's database through cooperative interactions. These experiences and knowledge include, of course, human responses and understanding of the data sonification results. Furthermore, in addition to humans, research is underway to allow machines to analyse the information embedded in sounds [39]. Thus, in addition to being communicated to humans, these sonification results will, in the future, be heard by robots that work in place of humans, which in turn will help these robots make judgements and decisions. In summary, we believe that the theory and practice of data sonification of film capacitors still deserve the research resources invested in them now and for some time to come.

Beneficiaries of data sonification of film capacitors. To answer the question 'Who are the sonification results for?', based on the previous content and with reference to the experimental results, inferences, and discussions of data sonification in other fields, the people who may benefit from the data sonification results of film capacitors and the specific aspects of the benefits are compiled as shown in Table 2. In addition to the benefits supported by the references mentioned above, we can boldly imagine that quality inspectors will gain a more user-friendly method to check the quality of numerous film capacitors. Even musicians can derive creative inspiration from the data sonification results of film capacitors.

The future directions. How to improve the sensitivity of sonification methods for handling data with small change characteristics is a worthy question in the future. To process larger-scale film capacitors data, methods to enhance the processing efficiency [42] with guaranteed accuracy [8, 33] should likewise be explored. In addition to adjusting the configuration of sonification parameters according to individual preferences, the development of sonification schemes for different data variation characteristics is also something that needs to be studied. What's more, a more complex melody would contain richer information than the current single melody, which would enhance the information transfer capability of the sonification method. In this process, making complex sonification results that highlight valid information [43–45] while reducing the interference from noisy information is also the question that film capacitor data analysts need to consider. The train of thought in this paper can also be applied in the observation of polymer films' experiments like helping us to record the breakdown time. On the contrary, mapping the sounds during the experiment into the data can be further work.

TABLE 2 Who are the sonification results for?

Beneficiary	Benefit	Ref.
Blind/visually impaired people	Access information about film capacitors through sound.	[10]
Students	Deepen the memory of knowledge related to film capacitors.	[11]
Monitor	Increase the probability of noticing changes in the state of film capacitors.	[23, 24]
Researchers	Enhance scientific discovery within complex datasets of film capacitors.	[32]
Producer	Improve the accuracy of film capacitor producers' operations.	[40]
Amateur	Reduce the requirements for observing, calculating, and even understanding scientific data.	[41]

4.2 | Conclusions

Long-term accumulation in the film capacitor industry has led to a wealth of data resources on film capacitors. Sonification offers new ideas for unlocking their potential value.

This paper presents a methodology and application framework for the sonification of film capacitor data, oriented to the five types of data tested, and the sonification results obtained accurately convey the data's main information.

Data with a monotonic change pattern (monotonic rise/monotonic fall) and data with a large difference in the values of the two data points before and after are easier to perceive in their sonification results.

In the case of film capacitor data with small numerical differences, the sonification results obtained based on the correspondence between numerical magnitude and pitch level are also difficult to distinguish them.

In addition to the fluctuation level of the data itself, the number of data points should also be taken into consideration when evaluating the volume of the data sonification results.

AUTHOR CONTRIBUTIONS

Yongxin Zhang: Conceptualization; data curation; software; visualisation; writing – original draft; writing – review & editing. **Difan Liu**: Software; visualisation; writing – original draft. **Xin-Yi Wei**: Conceptualisation; visualisation. **Xinjie Wang**: Writing – original draft; writing – review & editing. **Fangyi Chen**: Methodology; writing – review & editing. **Qikun Feng**: Writing – review & editing. **WenYuan Cao**: Conceptualisation. **Wen-Zhuo Dong**: Investigation. **Faisal Mehmood Shah**: Resources. **Yu-Xiao Liu**: Investigation. **Zhi-Yuan Wu**: Validation. **Jian-Tao Wang**: Writing – original draft. **Shaolong Zhong**: Writing – review & editing. **Zhi-Min Dang**: Funding acquisition; resources; supervision; writing – original draft; writing – review & editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no potential conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

1. Zhong, Z.M., et al.: Optimal planning of distributed photovoltaic generation for the traction power supply system of high-speed railway. J. Clean. Prod. 263, 121394 (2020). https://doi.org/10.1016/j.jclepro.2020.121394
2. Zhang, Y.X., et al.: Carbon emission and its reduction: from the perspective of film capacitors in the energy system. In: 2021 Annual Meeting of CSEE Study Committee of HVDC and Power Electronics (HVDC 2021), pp. 406–411. IET (2021). https://doi.org/10.1049/icp.2021.2596
3. Feng, Q.K., et al.: Recent progress and future prospects on all-organic polymer dielectrics for energy storage capacitors. Chem. Rev. 122(3), 3820–3878 (2021). https://doi.org/10.1021/acs.chemrev.1c00793
4. Zhang, Y.X., et al.: Study on fitting and prediction of metallized film capacitor's voltage drop. In: 22nd International Symposium on High Voltage Engineering, pp. 1796–1801. IET (2021). https://doi.org/10.1049/icp.2022.0175
5. Zhang, Y.X., et al.: Digital twin accelerating development of metallized film capacitor: key issues, framework design and prospects. Energy Rep., 2021 7, 7704–7715 (2021). https://doi.org/10.1016/j.egyr.2021.10.116
6. Zhang, Y.X., et al.: Data visualization of film capacitors. In: 2022 Tsinghua-IET Electrical Engineering Academic Forum, pp. 37–43. IET (2022). https://doi.org/10.1049/icp.2022.2093
7. Zhang, Y.X., et al.: Artificial intelligence aided design for film capacitors. In: 2022 IEEE International Conference on High Voltage Engineering and Applications, pp. 1–4. IEEE (2022). https://doi.org/10.1109/ICHVE53725.2022.9961843
8. Zhang, Y.X., et al.: Long-term capacitance variation characteristics, law extraction, single and collaborative prediction of film capacitors at room temperature and humidity. Microelectron. Reliab. 139, 114845 (2022). https://doi.org/10.1016/j.microrel.2022.114845
9. Bateman, C.: Understanding capacitors II. Electron. World 104(1742), 126–132 (1998)
10. Laconsay, C.J., Wedler, H.B., Tantillo, D.J.: Visualization without vision–how blind and visually impaired students and researchers engage with molecular structures. The Journal of Science Education for Students with Disabilities 23(1), 1–21 (2020). https://doi.org/10.14448/jsesd.12.0012
11. Cady, S.G.: Music generated by a Zn/Cu electrochemical cell, a lemon cell, and a solar cell: a demonstration for general chemistry. J. Chem. Educ. 91(10), 1675–1678 (2014). https://doi.org/10.1021/ed400584m
12. Paradiso, J.A., Gershenfeld, N.: Musical applications of electric field sensing. Comput. Music J. 21(2), 69–89 (1997). https://doi.org/10.2307/3681109
13. Qin, J., et al.: Flexible and stretchable capacitive sensors with different microstructures. Adv. Mater. 33(34), 2008267 (2021). https://doi.org/10.1002/adma.202008267
14. Marky, K., et al.: Let's frets! Assisting guitar students during practice via capacitive sensing. In: Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, pp. 1–12. ACM (2021)
15. Buys, K., Auvray, R.: Towards a discrete electronic transmission line as a musical harmonic oscillator. In: Proceedings of the Sound and Music Computing Conference 2013, pp. 569–575. SMC (2013)
16. Sirjani, R., Mohamed, A., Shareef, H.: Optimal capacitor placement in a radial distribution system using harmony search algorithm. J. Appl. Sci. 10(23), 2998–3006 (2010). https://doi.org/10.3923/jas.2010.2998.3006
17. Schenk, M.: The Sound of Computing. Thesis. University of Basel (2021)
18. Twotone: an open-source data sonification and data-driven music web app,(2022). Retrieved from https://github.com/sonifydata/twotone
19. Casado, J., et al.: SonoUno web interface for sonification and analysis of astrophysical data. In: 2nd Workshop on Astronomy beyond the Common Senses for Accessibility and Inclusion, pp. 122–125. RMxAC (2022)
20. Pitch (music), (2023), Retrieved from https://en.wikipedia.org/wiki/Pitch_(music)
21. Audio-waveform-for-data-sonification-results, (2024), Retrieved from https://github.com/xavi520/Audio-waveform-for-data-sonification-results
22. 1.capacitance, (2023), Retrieved from https://www.researchgate.net/publication/368305727_1capacitance
23. Hildebrandt, T., Hermann, T., Rinderle-Ma, S.: A sonification system for process monitoring as secondary task. In: 2014 5th IEEE Conference on Cognitive Infocommunications (CogInfoCom), pp. 191–196. IEEE (2014)
24. Jake, V., Guo, L.: Improving command and control cognition through complex data sonification. In: IIE Annual Conference. Proceedings, pp. 1109–1114. Institute of Industrial and Systems Engineers (IISE) (2019)

25. 2.voltage drop, (2023), Retrieved from https://www.researchgate.net/publication/368305732_2voltage_drop
26. 3.dielectric loss angle tangent, (2023), Retrieved from https://www.researchgate.net/publication/368307552_3dielectric_loss_angle_tangent
27. 4.absolute error, (2023), Retrieved from https://www.researchgate.net/publication/368307197_4absolute_error
28. 5.distribution digits for film capacitors' dielectric material types, (2023), Retrieved from https://www.researchgate.net/publication/368307615_5distribution_digits_for_film_capacitors'_dielectric_material_types
29. Flowers, J.H., Buhman, D.C., Turnage, K.D.: Data sonification from the desktop: should sound be part of standard data analysis software? ACM Transactions on Applied Perception (TAP) 2 4, 467–472 (2005). https://doi.org/10.1145/1101530.1101544
30. Li, W., Liu, Y., Xue, X.: Robust audio identification for MP3 popular music. In: Proceedings of the 33rd International ACM SIGIR Conference on Research and Development in Information Retrieval, pp. 627–634 (2010)
31. Russo, M., et al.: Improving Earth science communication and accessibility with data sonification. Nat. Rev. Earth Environ. 5, 1–3 (2024). https://doi.org/10.1038/s43017-023-00512-y
32. Zanella, A., et al.: Sonification and sound design for astronomy research, education and public engagement. Nat. Astron. 6(11), 1241–1248 (2022). https://doi.org/10.1038/s41550-022-01721-z
33. Zhang, Y.X., et al.: Theoretical Connection from the Dielectric Constant of Films to the Capacitance of Capacitors under High Temperature. High Volt. 8(4), 707–716 (2023). https://doi.org/10.1049/hve2.12308
34. Liu, D.F., et al.: High-temperature polymer dielectrics designed using an invertible molecular graph generative model. J. Chem. Inf. Model. 63(24), 7669–7675 (2023). https://doi.org/10.1021/acs.jcim.3c01572
35. Liu, D.F., et al.: Prediction of high-temperature polymer dielectrics using a Bayesian molecular design model. J. Appl. Phys. 132(1), 014901 (2022). https://doi.org/10.1063/5.0094746
36. Zhong, S.L., et al.: Prediction on the relative permittivity of energy storage composite dielectrics using convolutional neural networks: a fast and accurate alternative to finite-element method. iEnergy 1(4), 463–470 (2022). https://doi.org/10.23919/ien.2022.0049
37. Raabe, D., Mianroodi, J.R., Neugebauer, J.: Accelerating the design of compositionally complex materials via physics-informed artificial intelligence. Nature. Compu. Sci. 3(3), 198–209 (2023). https://doi.org/10.1038/s43588-023-00412-7
38. Zhang, Y.X., et al.: AI Safety of Film Capacitors. IET Nanodielectrics (2023). https://doi.org/10.1049/nde2.12071
39. Gorodnichenko, Y., Pham, T., Talavera, O.: The voice of monetary policy. Am. Econ. Rev. 113(2), 548–584 (2023). https://doi.org/10.1257/aer.20220129
40. Dreger, F.A., Rinkenauer, G.: Evaluation of different feedback designs for target guidance in human controlled robotic cranes: a comparison between high and low performance groups. Appl. Ergon. 116, 104204 (2024). https://doi.org/10.1016/j.apergo.2023.104204
41. Sawe, N., Chafe, C., Treviño, J.: Using data sonification to overcome science literacy, numeracy, and visualization barriers in science communication. Fronti. Commun. 5, 46 (2020). https://doi.org/10.3389/fcomm.2020.00046
42. Zhang, Y.X., Shen, H., Xu, S.T.: Cluster sampling for the demand side management of power big data. Int. J. N. Comput. Archit. their Appl. 6(4), 114–121 (2016). https://doi.org/10.17781/p002208
43. Oliveira, L.C., et al.: Generalizable semi-supervised learning strategies for multiple learning tasks using 1-D biomedical signals. In: NeurIPS 2022 Workshop on Learning from Time Series for Health (2022)
44. Pei, J.Y., et al.: All-organic dielectric polymer films exhibiting superior electric breakdown strength and discharged energy density by adjusting the electrode–dielectric interface with an organic nano-interlayer. Energy Environ. Sci. 14(10), 5513–5522 (2021). https://doi.org/10.1039/d1ee01960k
45. Ping, J.B., et al.: A bilayer high-temperature dielectric film with superior breakdown strength and energy storage density. Nano-Micro Lett. 15(1), 154 (2023). https://doi.org/10.1007/s40820-023-01121-6

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