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Calibration and testing of measurement devices at infrasound frequencies: proof from malfunctioning devices at site

Marvin Rust[1], Christoph Kling[1,*], Christian Koch[1], and Richard Barham[2]

[1] Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[2] Acoustic Sensor Networks, St Andrews Church, Warninglid RH17 5UB, UK

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Abstract – With the growing prevalence of infrasound and potential for annoyance comes the need for noise assessment. Performance validation of measuring instruments is an established necessity for reliable measurement data at conventional frequencies. However, infrasound measurements are critically dependent on the integrity of the microphone. A case study is presented showing that errors in excess of 20 dB result if the microphone diaphragm is perforated, and that such a defect cannot be detected by visual examination or with a typical sound calibrator. A further laboratory study validates the findings, and a scheme is proposed for identifying when such an issue exists.

Keywords: Infrasound, Sound pressure measurement, Measurement microphones, Noise assessment

1 Introduction

The urgent need for European and worldwide economies to make the transition to carbon-neutral energy production is well-known, and under continual discussion in the media [1]. As a first priority the change is essential for slowing climate change, but it also engenders a sustainable supply of energy for future generations. However, the production of renewable energy often creates unwanted environmental noise, especially low-frequency noise and infrasound (sound with frequency content below 20 Hz) [2, 3]. The prospect of increased noise nuisance can raise serious concerns and even objections by those living in the vicinity of planned facilities, and often obstructs the expansion and development of environmentally friendly energy production [4, 5]. Noise assessment, ideally founded on reliable measurements, therefore has an important mediating role in the development of new sites. In the vehement debate that usually ensues, such measurements must be objective, well-founded and able to withstand scrutiny by all sides. Therefore, the use of calibrated and approved measurement devices is indispensable [6, 7].

In other applications infrasound has a role in global security, in the monitoring of prohibited testing of nuclear weapons, and in other forms of geophysical monitoring including volcanology and early warning of earthquakes and tsunamis [8], in climate research as a means of studying the upper atmosphere [9], in extreme weather forecasting relating to hurricanes and storms [10], and in the study of glacier collapse [11]. Like the noise nuisance application described above, these geophysical applications also benefit from reliable infrasound measurements, though measurement systems utilising microbarometers are more common than measurement microphone-based systems in these applications. Microbarometers are not considered specifically here.

The foundation of measurement quality is that traceability to a primary realisation of the measurement quantity can be established, through an unbroken calibration chain. This must then be supplemented with a means of routinely validating the overall performance of the measuring instrument. In the conventional frequency range such an infrastructure already exists. Primary standards, with a history beginning in last century [12], are now well-established [13], and continue to evolve to extend the frequency range or accommodate new technologies [14–17]. Likewise, the performance verification process of measurement equipment is also well-developed: The IEC 61672-series of international standards [18] balances efficient test procedures and comprehensive evaluation of performance to guarantee that sound measuring instruments are fit-for-purpose. Measuring instruments validated in this way are then recognized in a legally binding manner.

However for infrasound, the infrastructure is only just being formulated with the development of new primary calibration methods [19, 20] and new international standardization activities [21, 22], while the development of a performance verification protocol for infrasound measuring instruments is just beginning [23]. However, in the case of conventional measurement systems such as sound level

*Corresponding author: christoph.kling@ptb.de

Figure 1. Photograph of the low frequency calibration system.

meters, there has been very little discussion about instrument performance specifications and test requirements for infrasound, and no consensus among experts on how to proceed exists.

Factors for consideration include the electrical response of the various time averaging and weighting functions, frequency filtering and weighting (noting the common A-weighting and C-weighting are not defined below 10 Hz) and environmental dependencies. However, aspects associated with the microphone will need particular attention, where in general, potential problems are more likely in the infrasound region. The microphone is effectively a sealed capsule where the pressure within remains at the ambient level while the diaphragm is deflected by the incident sound pressure. A controlled pressure equalization mechanism usually couples the internal volume to the exterior, but any dirt, deformations, material defect or damage that leads to a perforation of the diaphragm will have a profound impact on the low frequency response, causing a reduction in sensitivity. Furthermore, Jarvis has observed that electrostatic actuator methods typically use to check this frequency response do not detect the fault [24]. And the problem is more widespread than one might imagine; it is the case that many legacy models of microphone suffer from tiny perforations in the diaphragm as a matter of course. The problem may have been rectified with improved materials in more recent time, but it remains that a large proportion of microphone in service today are these older models. Since no method exists for checking the frequency response of sound measuring instruments before an on-site application, the risk is high that these potential faults remain unnoticed.

A study was therefore formulated to better understand the magnitude of the error that can be made. The study design consisted of two parts:

(a) An opportunistic field study, undertaken as part of a wider study assessing low frequency noise at a wind park. Test conditions were uncontrolled, but the data obtained could serve as a practical illustration of the potential for error and provide a first indication of error magnitudes.

(b) A laboratory study, based on the results of the field study, consisting of a systematic series of controlled measurements on the effects of perforation on the microphone frequency response.

It must be noted that this paper aims to demonstrate the impact of microphone defects on the quantitative assessment of low-frequency noise. This paper is not intended to show detailed analysis of the measurements shown.

2 Study of the impact of diaphragm perforation on the frequency response of a microphone in a field study

2.1 Low frequency calibration system

Both parts of the study rely on a specialized capability to calibrate the microphone systems in the low frequency range. Such a calibration system has recently been established at the Physikalisch-Technische Bundesanstalt (PTB) for both research and serving as a commercial calibration service. The calibration set-up is shown in Figure 1. It consists of a loudspeaker operated at low frequencies, coupled to the base of a long tube in which a reference device and the device to be tested can be placed. The calibration method uses the principle of pressure comparison calibration according to IEC 61094-5 [25]. The tube is approximately 1.4 m long to suit the long acoustic wavelengths, and the diameter is approximately 0.3 m which is large enough to accommodate a complete measuring instrument (e.g. a sound level meter), as necessary. The loudspeaker and tube have been designed to ensure a spatially homogeneous sound field distribution at the opposite end of the tube where the devices to be tested are located. The operational frequency range is 0.5–100 Hz, and calibrations have a reproducibility of about 0.03 dB. A calibrated Brüel & Kjær type 4160 laboratory standard microphone is used as a reference sensor.

2.2 Field study: practical measurements at a wind park

The opportunity was taken to evaluate the impact of particular defects in the measurement microphone, as a supplement to a planned survey of low frequency noise at a wind park in Saxony-Anhalt, Germany. The host study was to compare the efficacy of microphones and microbarometers as infrasound sensors. Details of the measurement configuration, techniques and findings, as well as

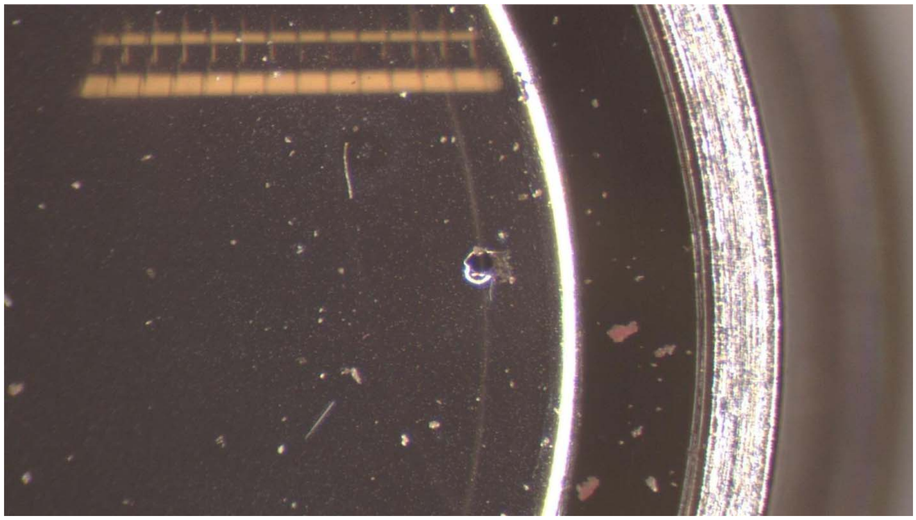

Figure 2. Photograph of the microphone diaphragm showing the hole in the diaphragm.

the main study data have been published elsewhere [26]. The purpose of the supplementary study reported here was to investigate the impact of perforations in the diaphragm of a microphone on field measurements of low-frequency environmental noise. It should be noted that while there was this opportunity care had to be taken to not to disrupt the execution of the host study, which limited the control of experimental conditions in practice. The study used a specially prepared microphone with an intentionally made perforation in the diaphragm. This was used alongside an intact microphone which was known to have the expected low-frequency response, as specified by the manufacturer.

The perforated microphone was prepared by using an old but flawlessly operating Brüel & Kjær type 4133 microphone capsule. This capsule was combined with a Brüel & Kjær type 2669 preamplifier and GRAS type 12AD microphone power supply to form a microphone system. Before affecting the perforation, the microphone system was calibrated in a frequency range from 2 Hz to 100 Hz. Then the microphone diaphragm was perforated using a stiff wire with a diameter of 100 μm. Figure 2 shows the perforation in the diaphragm. A performance check with a Brüel & Kjær type 4231 sound calibrator confirmed that the microphone was still operational. Interestingly, no change of level was detected at the calibration frequency of 1 kHz. The microphone system with the verified normal frequency response consisted of a Brüel & Kjær type 4964 microphone and GRAS type 26AK-S1 preamplifier, which was also calibrated to allow a direct comparison of the on-site measurements.

During these measurements both microphone systems were fitted with 90 mm diameter spherical windscreens and mounted approximately one meter above ground. Simultaneous measurements with both microphone systems were carried out and the results of the perforated and the intact microphone were compared.

The microphone signals were simultaneously captured using a Data Translation type DT9857E digitizer/logger and the uncompressed digital data was saved for offline evaluation. Obvious environmental disturbances and stop/start transients were removed from the recordings, leaving several 30-minutes-long segments of undisturbed data for analysis.

These raw data segments were fast Fourier transformed (sampling rate 2 kHz, window length 5 min, 50% overlap, Hann window) into the frequency domain. Corrections were applied to account for the known individual frequency responses of the microphones during calculation of sound pressure values from acquired voltage data. For the perforated microphone, the calibration data prior to inflicting the perforation was used for this procedure, simulating an undetected failure occurring after the last calibration of the system. Levels in third-octave bands conforming to IEC 61260-1 [27] were also computed to provide an absolute and comparable measure for the sound pressure levels acquired at the measurement site.

2.3 Field study findings

Figure 3 shows the third-octave band sound pressure levels and the narrowband frequency spectra of a typical result as an example. In this case, the measurement position was at a distance of about 480 m from the nearest wind turbine with medium wind velocity conditions (around 5 m/s). The results of the intact microphone system indicate a quite constant level as a function of frequency with no coherent signal component at the blade passing frequency (indicating that no thickness sound [28] was present). In contrast, the data of the perforated microphone system shows a deviation that increases approximately from 10 dB to 20 dB as the frequency decreases from 20 Hz to 10 Hz. During data analysis a calibration of the perforated microphone was made (see Fig. 7) and the comparison to the results before perforation confirmed a reduced sensitivity. The deviation was larger than expected from Figure 3 revealing that the signal-to-noise-ratio of the wind park measurements were already dominated by background and internal noise

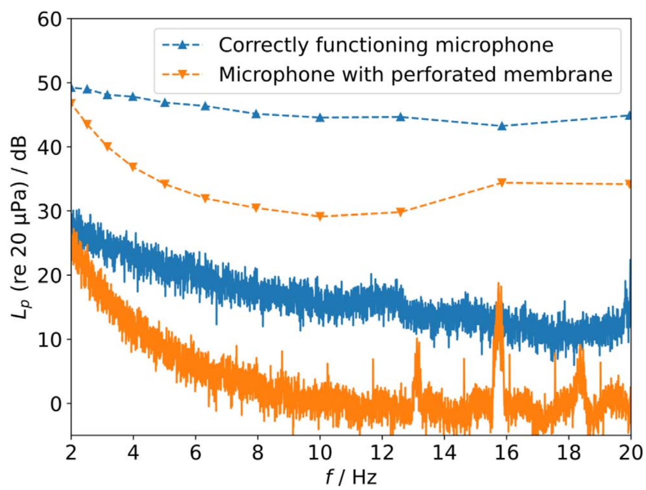

Figure 3. Third-octave levels (dashed) and narrow-band spectra (solid lines, frequency spacing df = 1/300 Hz) acquired in the vicinity of a wind park by a correctly functioning microphone and a microphone with a perforated diaphragm, distance to the wind park: 480 m, medium wind velocity of about 5 m/s, microphone height 1 m above ground.

sources. In addition, since the self-generated noise in the microphone increases with decreasing frequency, it is likely the reason for the uplift in the response below 10 Hz [29]. Peaks in the data from the damaged microphone are also apparent at frequencies around 13 Hz, 16 Hz, and 19 Hz that are less evident in the data of the intact microphone. A reason could simply be that the peaks are masked by the higher signal level produced with the correctly functioning microphone. Alternatively, the idea that the damage renders the perforated microphone more susceptible to extraneous disturbances cannot be excluded.

It should be emphasized that these results were obtained despite the sound calibrator check at 1 kHz indicated no issues with either system.

3 Detailed study of the impact of diaphragm perforation on the frequency response by a systematic investigation

3.1 Laboratory study: calibration during controlled stepwise perforation

The improvised preparation of the perforated microphone for the field study was not suited for a systematic investigation of the impact of perforations. To draw at least first quantitative conclusions a second Brüel & Kjær type 4133 microphone was selected for a study of the effect of controlled successive perforation of the diaphragm on the response of the microphone. The aim was to find some form of criterion for identifying microphones with a compromised low-frequency response, i.e. predicting the low-frequency roll-off for a known perforation area. For this purpose, a laser ablation system was applied to insert small holes of well-defined size successively into the microphone diaphragm. The microphone was recalibrated after each successive laser session.

The ablation laser system used to perforate the diaphragm was an industrial laser micro-machining system (GFH GmbH type GL.evo). Starting with one hole, the number of holes made in each session was approximately doubled. After 8 sessions the diaphragm had 71 holes in total. These holes formed an arc near the outer rim of the diaphragm. The perforations were placed near to the outer rim of the diaphragm to avoid the risk of short-circuiting contact between remnants of the damaged microphone diaphragm and the backplate electrode. The position of a defect in the diaphragm is not expected to have an influence on the frequency response due to the large wavelength at infrasound frequencies compared to any dimension of the microphone.

A microscope system was used to check the reproducibility of the perforation and to estimate the approximate diameters of the holes. These were in the range 19 ± 2 µm resulting in an area of about 2.8×10^{-4} mm^2 (compared to the diaphragm's total area of 75 mm^2). The laser produced a ring-like melting area around the holes with a maximum diameter of about 33 µm. The shape and the size of this zone may have an influence on the acoustic properties which could lead to an effective opening area that may differ from the actual area. Perforations with 19 µm diameter can barely be seen by eye, and a simple visual inspection of the microphone during use would not reveal any issue with the microphone. Figure 4 shows a close-up of one of the holes and an overview of the multiple holes placed on the rim of the microphone diaphragm. Figure 5 depicts a comparison of an intact (left) and a perforated diaphragm (centre) as seen by optical inspection using a microscope. The perforations cannot be visually detected. With special background illumination the holes become visible as small bright points (right). Furthermore, the protective grid must be removed to reveal this detail which is not normal in practice.

3.2 Detailed study findings

Figure 6 shows the change in the frequency responses determined by calibration after each perforation session, relative to the initial response of the microphone before perforation was started. The area of the 71 holes in total is approximately 0.02 mm^2, which is equivalent to a single hole of 160 µm diameter. Note that the hole applied in the field study had a diameter of at least 100 µm (the wire used had a diameter of 100 µm), which is not much smaller. The sensitivity decrease due to the perforation with 71 holes at 100 Hz is about −0.8 dB, whereas the decrease at 2 Hz amounts to about −21.0 dB.

For comparison to the microphone used in the field study, Figure 7 shows the absolute sensitivities for both microphone sets before and after the perforations were made. It can also be seen that the apparently smaller perforation of the field microphone leads to a much larger sensitivity loss compared to the laboratory microphone. A possible reason is that the wire used to perforate the diaphragm led to a larger and frayed hole than the wire

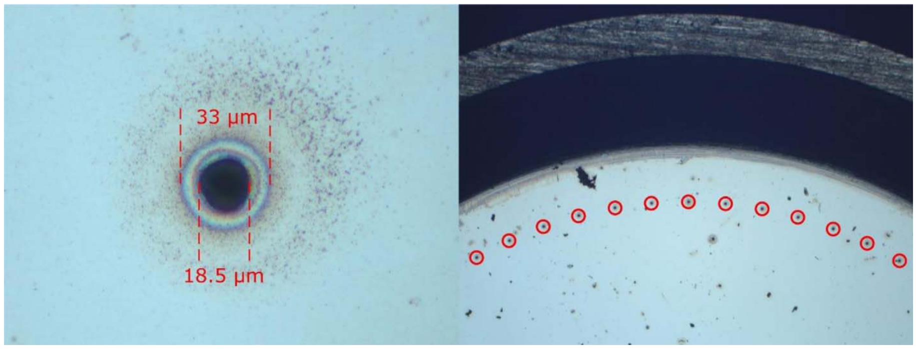

Figure 4. Photographs of the microphone diaphragm using a microscope after the manufacturing of all 72 perforations. Left: single hole with inner diameter of about 18.5 µm. Right: Multiple perforations are placed close to the rim of the microphone diaphragm on a circle in a distance to each other of about 370 µm. The holes are marked by circles for better visibility.

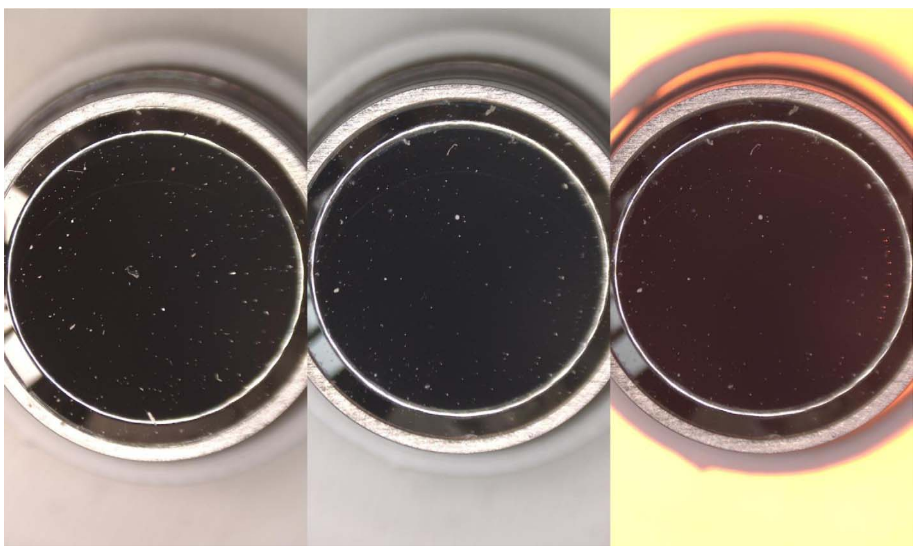

Figure 5. Visual inspection of two 1/2″-microphone diaphragms using a microscope. Left: A microphone with an intact diaphragm. Centre: A microphone with a diaphragm perforated by nine holes. Right: Same perforated microphone as in the centre but with light-through background illumination. Note the nine small bright points near the right side of the diaphragm.

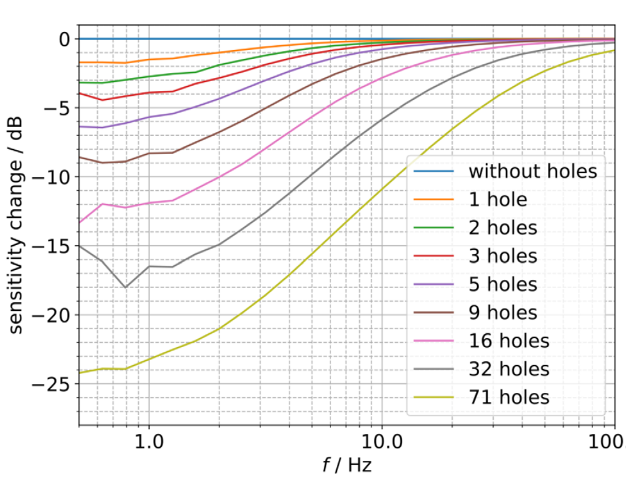

Figure 6. Sensitivity level of the perforated microphone relative to the initial calibration prior to adding perforations.

diameter would suggest. Unfortunately, the effective size of the perforation could not be measured optically. A comparison of the photographs in Figures 2 and 4 shows that controlling the perforation size using the wire puncture method is more difficult compared to using laser ablation.

As a supplement to full calibration, measurements were also made at each step with two regular sound calibrators; a Brüel & Kjær type 4231 operating at 1 kHz and a Brüel & Kjær type 4226 multi-frequency sound calibrator used at frequencies from 31.5 Hz to 1 kHz (the device itself operates up to 16 kHz). Both devices use sound pressure levels (SPLs) of 94 dB and 114 dB.

Compared to the initial measurement with no perforations, the indicated calibration value with 71 holes changed by −4.13 dB at 31.5 Hz, −0.22 dB at 250 Hz, and by just −0.01 dB at 1 kHz (using the 114 dB SPL setting). Such tests are the only capability which a technician may have for checking the microphone prior to use, using readily

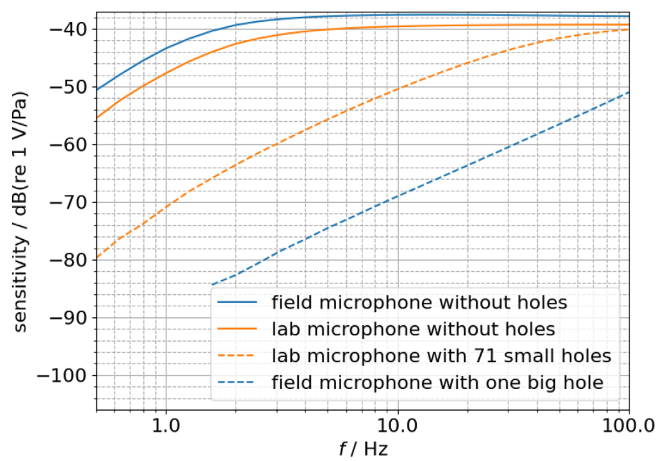

Figure 7. Absolute sensitivities of both microphones (field study and laboratory study) before and after the perforations.

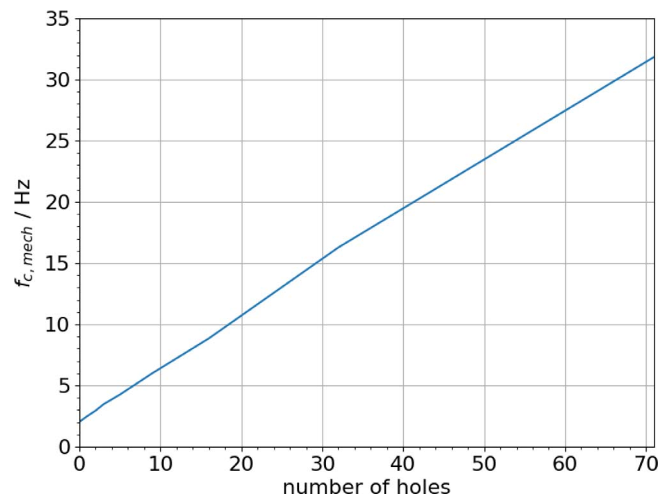

Figure 8. Cut-off frequency of the microphone cartridge due to the equalization vent over the number of holes inserted into the diaphragm.

available devices. They show how difficult it is to identify any fault because even at 250 Hz only a minimal difference in sensitivity occurs. If, however, the fault is not recognized, a deviation by potential perforation would directly influence the uncertainty of a measurement in the field. Since this contribution could be up to 20 dB or more it would clearly dominate all other uncertainty contributions. Thus, it is essential to identify potential perforations or other faults of this type before the measurement.

To quantify the change in sensitivity of the microphone due to the holes, its low-frequency response was approximated by a model describing the high-pass behaviour of the system. The sensitivity at low frequencies of a measurement microphone system consisting of a microphone cartridge and a preamplifier is mainly determined by two aspects. First, the equalization vent of the microphone cartridge attenuates the output signal at low frequencies. Second, the capacitance of the microphone cartridge and the input impedance of the preamplifier form an electrical high-pass filter. Both aspects can be modelled as first-order high-pass filters with a single cut-off frequency for each. Following this approach, a generic low-frequency model of a microphone system consisting of three parameters, the two cut-off frequencies of the high-pass filters describing mechanical and electrical effects and the absolute sensitivity of the microphone system at high frequencies, was developed. This model was fitted to the measured sensitivity curves after each perforation step using a least-squares approximation. It was found that the cut-off frequency of the filter describing mechanical effects had a linear dependency on the number of holes (see Fig. 8). For the intact diaphragm, the cut-off frequency of the mechanical filter was 2 Hz, which matches the manufacturer specification for this particular type of microphone cartridge. The cut-off frequency of the electrical high-pass filter was nearly constant 0.58 Hz, which also matches the manufacturer specifications for the particular combination of microphone cartridge and preamplifier. The determined sensitivity of the microphone set showed a slight decrease of less than 0.5 dB with increasing number of holes.

The linear dependence of the mechanical cut-off frequency of the cartridge indicates that additional holes or defects in the diaphragm seem to increase the connection between the space behind the diaphragm and the outside of the microphone. This could be interpreted as a frequency dependent effective size of the equalization vent. Since it can be assumed that many diaphragms have at least micro-perforations, this could be a novel parameter for characterising existing microphones.

4 Discussion and conclusions

Sound measurements are often required for compliance with noise control schemes, legal disputes or socio-economic purposes. Examples are occupational safety [30], management of noise at airports [31] or protection against general noise-related health effects [32]. Although still only covered by national regulations or standards [33, 34], noise measurement is an important consideration in renewable energy generation. Characterizing the low frequency sound and infrasound components is a generally unfamiliar territory for noise measurement practitioners, who will need appropriate tools and guidance, and a supporting test-and- calibration infrastructure to operate effectively.

This study has indicated the following elements which should be considered when practically checking the integrity of an infrasound measurement microphone.

(a) Errors in measurement can be significant if the defect in the microphone is not identified. The study has shown that errors of around 20 dB are possible. Since typical uncertainties are of the order of tenth of decibels for instrument calibration and typical around 3 dB for on-site contributions, undetectable errors of 20 dB are completely unacceptable and negate the original intent of assessing the noise.

(b) The conventional pre-deployment check of the sound measurement system with a sound calibrator does not detect microphones with small perforations in the diaphragm, that have a significant impact on the measurements in the infrasound region.
(c) Visual inspection of the diaphragm surface is also likely to be ineffective at identifying potential damage, especially when a small, harmless speck of contamination can easily be mistaken for a hole, and vice versa.
(d) A multi-frequency sound calibrator offers a partial solution for checking the microphone system frequency response but does not extend into the infrasound frequency range. Measurements at available frequencies may not have sufficient resolution to indicate problems in the lower frequency range. Multi-frequency sound calibrators can also be cumbersome for field use and add significantly to the efforts needed to install a system.

By now, the only safe solution is to have the measurement system fully calibrated in the infrasound frequency range, at a calibration laboratory. Even so, suitable calibration services are only just beginning to emerge.

This study therefore identifies a clear need for a field calibrator operating in the infrasound region, that can be used to check the integrity of the microphone, exactly mirroring the practice used for measurements in the conventional frequency range. While the specification of such a sound calibration is beyond the scope of this article, a key parameter to be decided is the operating frequency or frequencies. There are difficulties in operating a device if the frequency is set as low as 1 Hz or 2 Hz, especially in the field. However, Figure 6 shows that the frequency response relating to a given hole size is quite predictable. Such curves could then provide the basis for extrapolating the response at a moderate frequency in the infrasound range, as potentially provided by the low-frequency sound calibrator, to the more extreme low frequencies. The response with the low frequency calibrator could then be determined at the time of calibration and checked prior to measurements. Response curves like those in Figure 6 could then be used to estimate the error at the lowest frequency of interest based on any deviation of its response observed with the low frequency calibrator. A criterion for the maximum allowable deviation could also be imposed to limit the maximum error. Remember though that the data in Figure 6 has been normalized to the response of the microphone in its undamaged state, which itself has a low-frequency roll-off due to the pressure equalization vent and to the performance of the preamplifier. The measurement uncertainty will be impacted by such a procedure, but this is likely to be relatively insignificant in the practical measurement of infrasound.

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Conflict of interest

Authors declared no conflict of interests.

References

1. E. Murphy: What to do about environmental noise? Acoustics Today 13, 2 (2017) 18–25.
2. I. van Kamp, F. van den Berg: Health effects related to wind turbine sound, including low-frequency sound and infrasound. Acoustics Australia 46, 1 (2018) 31–57. https://doi.org/10.1007/s40857-017-0115-6.
3. F. van den Berg, I. van Kamp: Audibility and health effects of infrasound, in: 9th International Conference on Wind Turbine Noise (WTN 2021), Online, 18–21 May 2021, Curran Associates Inc, Red Hook, NY, 2021, pp. 492–498.
4. M. Sonnberger, M. Ruddat: Local and socio-political acceptance of wind farms in Germany. Technology in Society 51 (2017) 56–65. https://doi.org/10.1016/j.techsoc.2017.07.005.
5. K. Langer, T. Decker, J. Roosen, K. Menrad: Factors influencing citizens' acceptance and non-acceptance of wind energy in Germany. Journal of Cleaner Production 175 (2018) 133–144. https://doi.org/10.1016/j.jclepro.2017.11.221.
6. S.E. Keith, K. Feder, S.A. Voicescu, V. Soukhovtsev, A. Denning, J. Tsang, N. Broner, W. Richarz, F. van den Berg: Wind turbine sound power measurements. Journal of the Acoustical Society of America 139, 3 (2016) 1431–1435. https://doi.org/10.1121/1.4942405.
7. L. Gaßner, E. Blumendeller, F.J.Y. Müller, M. Wigger, A. Rettenmeier, P.W. Cheng, G. Hübner, J. Ritter, J. Pohl: Joint analysis of resident complaints, meteorological, acoustic, and ground motion data to establish a robust annoyance evaluation of wind turbine emissions. Renewable Energy 188 (2022) 1072–1093. https://doi.org/10.1016/j.renene.2022.02.081.
8. J. Marty: The IMS infrasound network: current status and technological developments, in: A. Le Pichon, E. Blanc, A. Hauchecorne (Eds.), Infrasound monitoring for atmospheric studies, 2nd ed. Springer, Cham, 2018, pp. 3–62.
9. J.D. Assink, R. Waxler, W.G. Frazier, J. Lonzaga: The estimation of upper atmospheric wind model updates from infrasound data. Journal of Geophysical Research: Atmospheres 118 (2013) 10707–10724. https://doi.org/10.1002/jgrd.50833.
10. B.R. Elbing, C.E. Petrin, M.S. van den Broeke: Measurement and characterization of infrasound from a tornado producing storm. Journal of the Acoustical Society of America 146 (2019) 1528–1540. https://doi.org/10.1121/1.5124486.
11. G.B. Deane: The underwater sound of glacers. Acoustics Today 15, 4 (2019) 12–19.
12. A.L. DiMattia, F.M. Wiener: On the absolute pressure calibration of condenser microphones by the reciprocity method. Journal of the Acoustical Society of America 18, 2 (1946) 341–344.
13. J. Avison, R. Barham: Final report on key comparison CCAUV.A-K5: pressure calibration of laboratory standard microphones in the frequency range 2 Hz to 10 kHz. Metrologia 51, 1A (2014) 9007.

14. R. Barham, S. Barrera-Figueroa, J.E.M. Avison: Secondary pressure calibration of measurement microphones. Metrologia 51, 3 (2014) 129.
15. S. Barrera-Figueroa: Free-field reciprocity calibration of measurement microphones at frequencies up to 150 kHz. Journal of the Acoustical Society of America 144, 4 (2018) 2575–2583.
16. A. Prato, N. Montali, C. Guglielmone, A. Schiavi: Pressure calibration of a digital microelectromechanical system microphone by comparison. Journal of the Acoustical Society of America 144, 4 (2018) EL297–EL303.
17. R.P. Wagner, S.E. Fick: Pressure reciprocity calibration of a MEMS microphone. Journal of the Acoustical Society of America 142, 3 (2017) 251–257.
18. IEC 61672: Electroacoustics – Sound level meters. https://webstore.iec.ch/publication/5708.
19. 19ENV03 Infra-AUV: Metrology for low-frequency sound and vibration: infrasound primary methods, 2020. Available at https://www.ptb.de/empir2020/infra-auv/information-communication/background/infrasound-primary-methods/.
20. P. Vincent, D. Rodrigues, F. Larsonnier, C. Guianvarc'h, S. Durand: Acoustic transfer admittance of cylindrical cavities in infrasonic frequency range. Metrologia 56, 1 (2019) 15003.
21. IEC 61094–2:2009+AMD1:2022: Electroacoustics – Measurement microphones – Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique. https://webstore.iec.ch/publication/74047.
22. IEC TR 61094–10:2022: Electroacoustics – Measurement microphones – Part 10: Absolute pressure calibration of microphones at low frequencies using calculable pistonphones. https://webstore.iec.ch/publication/29863.
23. C. Kling, C. Koch, M. Rust, R. Barham, D. Rodrigues, S. Barrera Figueroa, E. Sandermann Olsen: Specifications and testing strategies for measurement devices for noise exposure determination in the infrasound frequency range, PTB Open Access Repository, 2021. Available at https://oar.ptb.de/resources/show/10.7795/EMPIR.19ENV03.RE.20210609
24. D.R. Jarvis: The accuracy of the electrostatic actuator method of determining the frequency response of condenser microphones. Journal of Sound and Vibration 123, 1 (1988) 63–70.
25. IEC 61094–5:2016: Electroacoustics – Measurement microphones – Part 5: Methods for pressure calibration of working standard microphones by comparison. https://webstore.iec.ch/publication/24988.
26. M. Rust, C. Koch: Microphone measurements in the vicinity of wind power plants: Results for the wind park in Gagel, Saxony Anhalt, Germany. PTB Open Access Repository, 2021. Available at https://oar.ptb.de/resources/show/10.7795/720.20211130.
27. IEC 61260-1:2014: Electroacoustics – Octave-band and fractional-octave-band filters – Part 1: Specifications. https://webstore.iec.ch/publication/5063.
28. O. Marcillo, S. Arrowsmith, P. Blom, K. Jones: On infrasound generated by wind farms and its propagation in low-altitude tropospheric waveguides. Journal of Geophysical Research: Atmospheres 120, 19 (2015) 9855–9868.
29. Bruel & Kjaer: Microphone handbook, volume 1: theory (BE 1447-12), 2019. Available at https://www.bksv.com/media/doc/be1447.pdf.
30. B. Goelzer, C.H. Hansen, G.A. Sehrndt: Occupational exposure to noise: evaluation, prevention and control. World Health Organization, Dortmund, Germany, 2001.
31. International Civil Aviation Organization: Guidance on the balanced approach to aircraft noise management (ICAO 9829), 2nd edn. ICAO, 2008.
32. D. Jarosińska, M.-È. Héroux, P. Wilkhu, J. Creswick, J. Verbeek, J. Wothge, E. Paunović: Development of the WHO environmental noise guidelines for the European region: an introduction. International Journal of Environmental Research and Public Health 15, 4 (2018) 813. https://doi.org/10.3390/ijerph15040813.
33. DIN 45680:1997-03: Messung und Bewertung tieffrequenter Geräuschimmissionen in der Nachbarschaft. (English title: Measurement and assessment of low-frequency noise emissions in the neighbourhood). https://www.beuth.de/de/norm/din-45680/2917742.
34. A.T. Moorhouse, D.C. Waddington, M.D. Adams: A procedure for the assessment of low frequency noise complaints. Journal of the Acoustical Society of America 126 (2009) 1131–1141.

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