

# A low-frequency noise measurement and recording device for occupant operation

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## ABSTRACT

There are often several challenges involved with measuring low-frequency noise and infrasound in dwellings. A main challenge is that standing waves make the measurements very dependent on the microphone position. Furthermore, the low-frequency-noise source may be unknown and in some cases, the noise is only present intermittently and maybe worse at night which makes measurements done by consultants or researchers troublesome. In order to deal with these challenges, a low-frequency measurement device was developed. The device is easy to use for the occupants of dwellings, and if they follow simple guidelines they can make representative recordings of low-frequency noise. When the device is connected to the internet, the recordings and pictures of the measurement setup are automatically uploaded to a central server, for further analysis and assessment. This analysis can assist in identifying noise sources and serve as a reference for further investigation. The paper deals with the construction and detailed low-frequency calibration of the device. It has proven successful in capturing low-frequency noise from various sources like heat pumps, cooling systems and wind turbines, and experiences and measurements from some of these cases are presented.

## 1 INTRODUCTION

Low-frequency noise is a common cause of annoyance and potential sleep disturbance in dwellings. The sound propagates further and house insulation does not attenuate as much as at higher frequencies, which means that noise in dwellings from external sources is dominated by low-frequency components.

At Aalborg University, we are regularly contacted by frustrated people who experience a humming noise in their homes without a solution to their problem. In many cases, the local authorities do not have the equipment/expertise/willingness to investigate their claims, or noise measurements do not show high enough levels for further exploration and attempts to solve the problem. A likely explanation for the measurements showing low-levels is that they are not representative for the actual low-frequency noise that the occupant experience. Another explanation can of course be that the occupant is indeed very sensitive - there is an individual variation as to what noise levels are acceptable, and noise limits do not protect 100% of the population. In some cases, it may be communication problems, as noise is "invisible" and not easy to describe for the layman, and may e.g. not necessarily be a low-frequency noise. Finally, a possibility is low-frequency tinnitus, which was seen in some cases in a larger study (Pedersen, Møller, and Wayne 2008). However, without representative measurements it is not possible to properly assess and solve the problem.

To make representative measurements of the low-frequency noise in dwellings can be very challenging for several reasons. The main challenges are that standing waves make the measurements very dependent on the microphone position and specialized equipment and expertise is needed. Furthermore, the low-frequency-noise source may be unknown and in some cases, the noise is only present intermittently and maybe worse at night which makes measurements done by consultants or researchers troublesome.

### 1.1 Low-frequency sound field in dwellings

At low frequencies, standing wave patterns dominate the sound field inside dwellings (Pedersen, Møller, and Persson-Way 2007). The actual shape of the pattern depends on parameters like the dimensions of the room, the wavelength of the sound, how and where the sound is transmitted into the room and how rigid and absorbing the surfaces are. This makes it difficult or impossible to predict the pattern even for experts. To illustrate the sound field caused by standing waves a finite-difference-time-domain (FDTD) simulation of a low-frequency noise (cooling compressor recording) exciting a room is seen in Figure 1. The main low-frequency component of the noise is a 47-48 Hz tonal component that is slightly modulated but on average the standing wave pattern is relatively stable and dominates the level distribution in the room. The sound pressure level (SPL) in the shown

horizontal plane varies up to about 20 dB depending on position. There are large areas with high levels of the tone, but there are also distinct dips and a relatively large low-level area close to the middle of the room. If the measurement microphone is placed here, then the level of the low-frequency noise will be considerably underestimated. Therefore, it is crucial to avoid dips in the standing wave pattern when positioning the microphone if the purpose of the measurements is to find potential annoying sounds. Figure 1 is just a simulation to illustrate the problem, but it reflects well what may occur in real life and match the experience from measurements in rooms (Pedersen, Møller, and Persson-Waye 2007) and in real low-frequency noise cases (Pedersen, Møller, and Waye 2008).

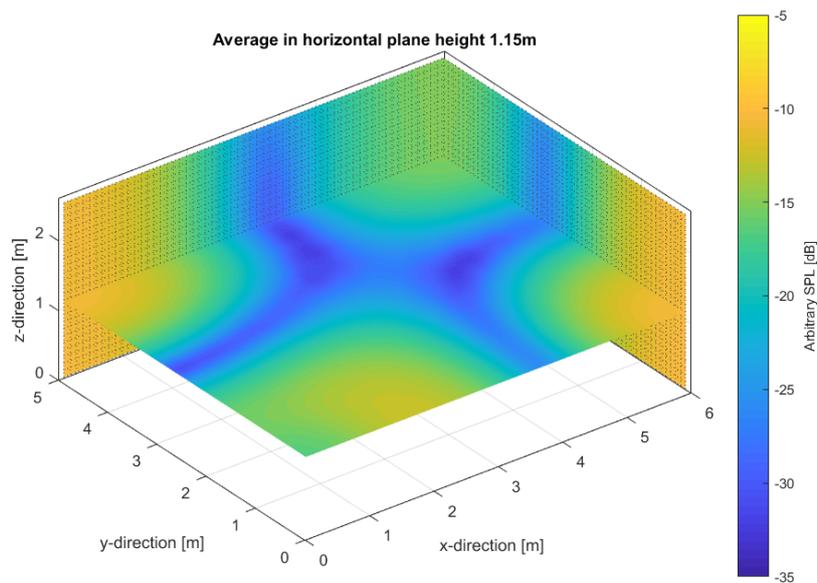


Figure 1: Example of an FDTD simulation of the sound field in a room with dimensions (6.0x5.0x2.6 m) excited by the noise from a cooling compressor. The arbitrary SPL is shown for the farther walls and a plane at height 1.15 m. The noise is dominated by a strong 47-48 Hz component, which is responsible for the clear standing wave pattern where the SPL varies up to 20 dB depending on position.

## 1.2 Low-frequency measurement procedures

Different countries have different low-frequency noise measurement and assessment procedures, that to some extent, attempt to alleviate the issue of standing waves by using more than one measurement position, like Denmark (Miljøstyrelsen 1997) and Sweden (Simmons 1996). Unfortunately, this is with limited success as there is a significant risk of underestimating the low-frequency noise in the dwelling with these procedures (Pedersen, Møller, and Persson-Waye 2007), (Pedersen, Møller, and Waye 2008).

For the uninformed, it may seem a trivial task to measure the noise by placing the microphone where the occupant informs that the noise is annoying. However, if this position is not carefully selected and simply put nearby, or in the general area appointed by the occupant there is a great risk of unintentional placement at a dip in the standing wave pattern of the dominating low-frequency component.

The sound level meter used for low-frequency noise measurements should be suitable and calibrated also at low frequencies. General sound level meters typically show only the broadband A-weighted SPL that does not offer much guidance for finding a representative microphone placement. Using the broadband A-weighting the level may be dominated by higher frequency sounds and not show the high levels of the low-frequency noise components as seen in the left of Figure 2. When using the A-weighted level for guiding low-frequency noise measurements it is important to avoid the bias of higher frequencies and a solution could be to low-pass filter before calculating the A-weighted level as seen to the right in Figure 2. Here the noise is low-pass filtered with upper frequency of 180 Hz. In this case, the high-frequency biasing of the A-weighting is alleviated and the clear standing wave pattern of the 47-48 Hz dominates the displayed level, albeit not as clearly as in the case with no A-weighting (see Figure 1), since 73 Hz and 100 Hz components in the noise start to appear.

Notice in Figure 1 that the extreme corners also contain the high levels, which makes these positions a good alternative to scanning as suggested by (Pedersen, Møller, and Persson-Waye 2007).

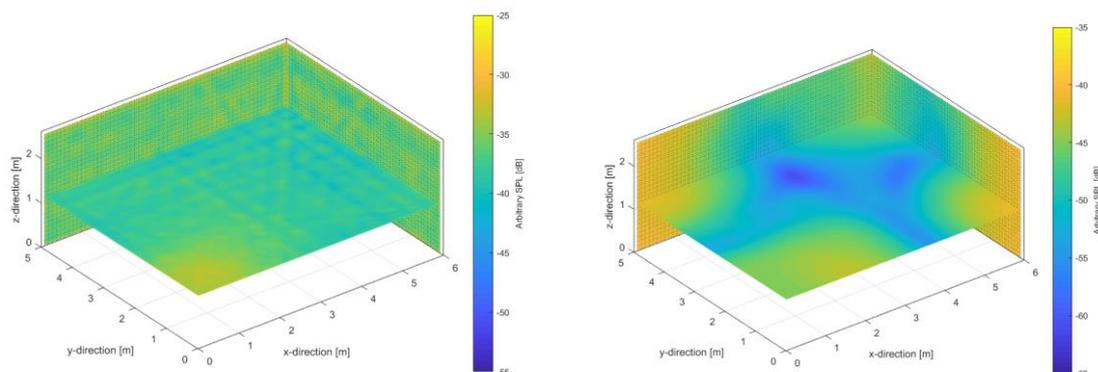


Figure 2: Left: FDTD simulation of the sound field in a room with dimensions (6.0x5.0x2.6 m) excited by the noise from a cooling compressor A-weighted and low-pass filtered with upper frequency of 1000 Hz. The arbitrary SPL is shown for the farther walls and a plane at height 1.15 m. Right: FDTD simulation in the same room and noise, but with a low-pass filter upper frequency of 180 Hz.

### 1.3 Dealing with the challenges of low-frequency noise measurements in dwellings

Motivated by an attempt to deal with the mentioned challenges and make low-frequency noise measurements widely available a custom-made device was developed at Aalborg University.

The device is carefully calibrated for the entire low-frequency range. The occupants can use the device themselves, and following simple guidelines, they can make recordings, at times, when the low-frequency noise is representative for what they experience. The occupants are instructed to use their ears, but are also assisted by a simple LED meter on the device to find a representative recording position. The device only shows the contribution of the low-frequency part of the noise (<180 Hz) on the LED-meter, but records the whole frequency range. A camera that can be used for photo documentation of the measurement setup accompanies the device. When the camera is connected to the device via USB, the photos are collected on the device together with the sound recordings. Recordings and pictures of the measurement setup are automatically uploaded to a central server. An analysis of the recordings can guide an expert discovering what the noise source is. Listening and spectral analysis can assist in finding the noise source, when the expert visits the location. It is especially helpful to know what frequency components to search for.

## 2 METHODS

### 2.1 Low-frequency measurement device construction

The low frequency measurement device (see Figure 3) is based on the Raspberry pi platform (Raspberry Pi 1, Model B) connected to a USB measurement microphone (see section 2.2 for more details on the microphone). It is running a Linux distribution (Linux pi2 3.6.11+) and sample acquisition is using the ALSA API ([https://www.alsa-project.org/main/index.php/Main\\_Page](https://www.alsa-project.org/main/index.php/Main_Page)) at 16-bit resolution and 48 kHz sampling frequency.

Great care was taken to only include relevant buttons and information on the device to make operation as simple as possible for the occupant to initiate a recording and storing it afterwards. There are no settings and therefore no risk of mistakes in operating the device. This means that the device changes mode according to what it is connected to. When the USB microphone is connected the device is in measurement mode, when the camera is connected new pictures are automatically transferred to the device, and when an Ethernet cable with internet is connected, pictures and recordings are automatically uploaded to Aalborg University servers using the standard rsync UNIX command.

When in measurement mode there is a continuously updated LED meter, which covers the A-weighted SPL below 180 Hz which is the frequency range used for low-frequency noise assessment according to the Danish guidelines (Miljøstyrelsen 1997). The measure used,  $L_{pA,LF}$  is defined as the combined A-weighted SPL for the 10-160 Hz third-octave bands. The low-frequency noise limits in Denmark are 20 dB for evening/night and 25 dB in the daytime – there is no penalty for tones or impulse noise. The level range covered on the LED meter is from 12 to 35 dB  $L_{pA,LF}$ .

If the occupant pushes the start button, a two-minute broadband recording is initiated.

The device has a hardware real time clock with battery supply, so that time and date is retained between power-downs. The main battery supply is a lithium-ion battery, which is recharged through a standard 5 V microUSB charger, and can keep it operational for several hours between charges. Battery level can be inspected on the backside of the device by the push of a button.



Figure 3: Left: The low-frequency measurement device with a simple user interface (in Danish).

Middle: the USB measurement microphone (Dr. Jordan ATD-4S) with a windshield.

Right: The custom-made microphone calibrator consisting of a tweeter with a closed front volume and space for two symmetrically placed microphones.

## 2.2 Microphone and microphone calibration

The microphone is a Dr. Jordan ATD-4S ½-inch pre-polarized condenser measurement microphone, which is a USB microphone with built-in AD converter. It has two channels, where channel 1 is an attenuated (-26.8 dB) version of channel 2 which can be used if channel 2 is overloading. Both channels are always recorded.

The microphone is not factory-calibrated at low frequencies and it is important to be able to measure the frequency response regularly in order to ensure calibrated measurements. It was deemed important that the frequency response should be calibrated in the entire frequency range from 1 kHz and below, which means that even specialized equipment like a B&K 4221 high-pressure calibrator cannot be used, as it does not cover such a wide frequency range in a single mode. Therefore, a custom-made microphone calibrator was constructed consisting of a ½" cone tweeter unit (Peerless 801771) and a small front volume with symmetric placement of two microphones (see right Figure 3). In order to ensure a relatively flat frequency response up to above 1 kHz a tweeter with a resonance frequency above this was chosen. The calibrator has a relative flat frequency response below approx. 2 kHz – at higher frequencies the volume inside the calibrator is no longer a pressure field and therefore it is not usable in this frequency range.

Calibration measurements are done using a custom-made Matlab calibration platform with a USB sound card (Roland Quad Capture) controlled through ASIO drivers with playrec (<http://www.playrec.co.uk/>). The power amplifier used to drive the calibrator is a Rotel 976 mk II that has been modified to have a lower 3 dB limiting frequency of approx. 1.6 Hz, fixed gain setting and a much lower noise floor.

The transfer-function of the calibration chain is measured using a reference microphone (B&K 4193) on a 01 dB Symphonie measurement system, which has a lower limiting frequency below 1 Hz. This reference system is also used for reference control during calibrations to verify the SPL generated inside the calibrator.

The method used for measuring transfer functions is the swept-sine technique (Müller and Massarani 2001) with a logarithmic sweep of 10 s duration. The long duration and a playback level in the order of 100 dB ensures a good signal to noise ratio also at low frequencies.

Calibration of the devices is performed by placing the measurement microphone in the calibrator and recording the logarithmic sweep on the device. Additionally, pure tones at the third-octave-band center frequencies from 10 to 200 Hz are produced at 94 dB in a sequence inside the calibrator and recorded in the same file. This serves as a double check of the measured transfer-function. The recording containing the sweep and pure tones are transferred from the device and used in the custom-made calibration software to extract the transfer-

function (corrected for the transfer-function of the whole calibration chain). From this transfer-function third-octave-band frequency sensitivity data are calculated (see Figure 4) and stored in a calibration file. The device is calibrated regularly and the calibration file is used for performing a calibrated third-octave-band analysis of the recordings (see section 2.4).

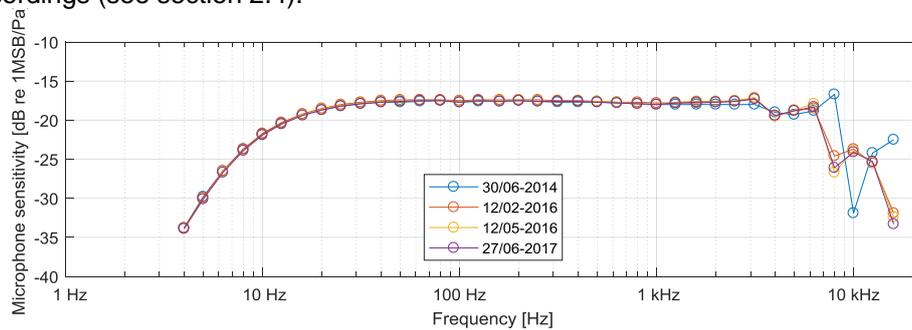


Figure 4: Measured microphone frequency response using the custom-made calibrator over a time period from 2014-2017. The measurements are valid below 2 kHz. For frequencies above 2 kHz, the calibrator front volume does not act as a pressure field, and data at these frequencies should be disregarded. As the microphone includes an AD-converter, the sensitivity is shown in dB relative to maximum digital level pr. Pascal (dB re 1 MSB/Pa).

The noise-floor of the microphone is measured inside a rigid sphere, through a hole fitting the microphone with an airtight seal around. This is placed in a quiet laboratory at Aalborg University and a recording is initiated. Figure 5 shows a third-octave-band analysis of the noise floor, which is sufficiently low for low-frequency noise measurements.

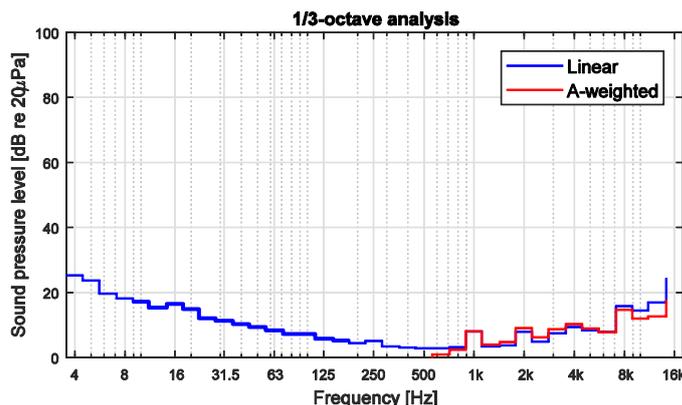


Figure 5: A Third-octave band analysis of the noise floor of the microphone.  $L_{pA,LF}$  is -4.3 dB.

### 2.3 Measurement procedure for occupants

An instruction manual with pictures and guidelines for doing low-frequency noise measurements is included in the flight-case with the device in order to ensure as representative measurement as possible, given the fact, that it is laypersons i.e. the occupants that carries out the measurements.

A very condensed and translated version of the guidelines with the main points is given in the following:

*When to measure? Carry out the measurements when the noise is prevailing and representative for the annoying noise situations.*

*Where to measure? Measure in the rooms where the noise is most annoying. Inside the room use the ears to pinpoint positions where you head is positioned when the noise is most annoying. Positions must represent normal use of the room. These exact positions should be where the microphone is placed.*

*If the noise is most annoying with closed windows, then it is important to keep them closed during measurements (this is also part of the Danish Guidelines on low-frequency noise (Miljøstyrelsen 1997)).*

*The microphone stand should be used to keep the microphone firmly positioned.*

*Before measurements it is important to turn off the main power to the building - a flashlight is included in the flight-case.*

*Check the scale on the LED meter and take note of the dB value, or range if the level is fluctuating.*

*Start recording on the device and say briefly where you are recording and give other relevant information, like if the windows are open, the noise is especially annoying etc. Then leave the room and close the door. Keep*

completely silent and after two minutes you can enter the room again. If there had not been any disturbances then store the recording.

After each recording, use the supplied camera to take a picture of the microphone and how it is placed in the room.

Perform recordings in several positions inside the room and in different rooms.

When having finished the recordings connect the camera to the device. The pictures are automatically transferred from the camera to the device through a USB connection.

Then connect the device to the internet through the supplied Ethernet cable, and the pictures and the recordings are automatically uploaded to Aalborg University.

## 2.4 Analysis

A semi-automated analysis is implemented in Matlab and generates a one-page report in A4 format with a third-octave-band analysis and calculated A-weighted and  $L_{pA,LF}$  from the recordings. It requires specification of the time window of the analysis, as the initial part after the occupant has started the recording should be excluded of the analysis window.

Optional for the A4 report is a picture of measurement setup, an overlay of narrow band frequency analysis and a figure showing wind speed at the nearest meteorology station (if available).

## 3 RESULTS FROM THREE LOW-FREQUENCY NOISE CASES

The device has been used in several cases where occupants have complained about low-frequency noise in their home. The following three cases are examples of these.

### 3.1 Cooling compressor noise case

In this case the occupant lives in an apartment next to a restaurant and the outlet from the cooling compressors in the basement of the restaurant is mounted on the wall next the occupant's window. The occupant has used the device to make more than 20 recordings, representing different times (day, evening and night), locations (different rooms in the apartment, in the hallway outside the apartment and outside the backdoor of the restaurant) and different perceptual characteristics of the noise (mentions specific hum on one recording).

A spectrogram of the worst-case recording in a room in the apartment can be seen in Figure 6 left. The mid-frequency content in the beginning of the spectrogram is the occupant speaking to inform about the recording position. This is followed by some impulse sounds that show up as vertical lines in the spectrogram. These are footsteps followed by the sound of the door closing. There is a clear dominating tonal component around 47-48 Hz that fluctuates in frequency and level. Notice that the level of the dominating low-frequency component around 48 Hz increases in level when the door is closed. This is probably the result of reflections from the closed door contributing to the standing wave pattern inside the room. When the door is open in the beginning of the recording, the standing wave pattern is different.

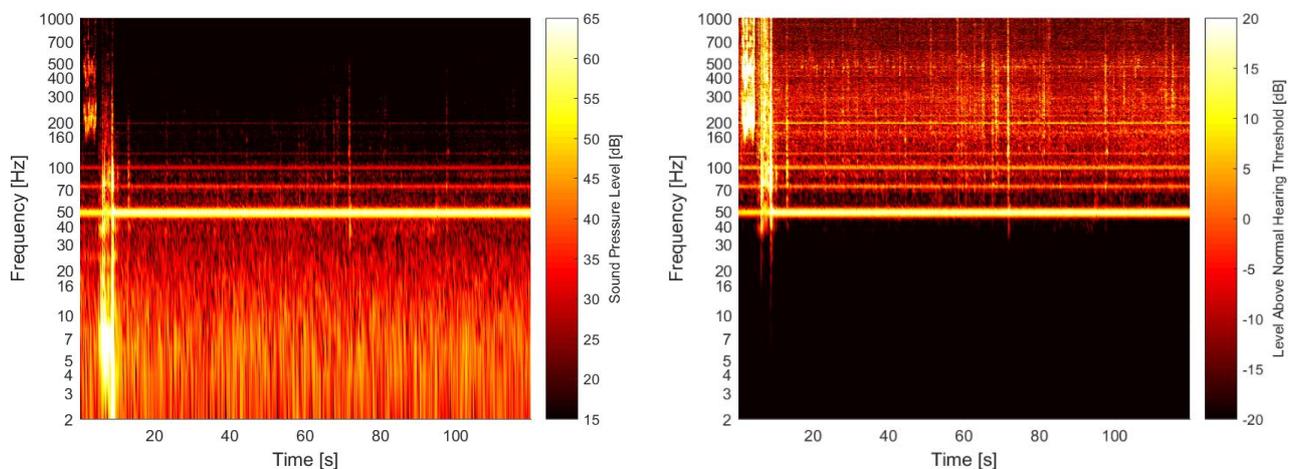


Figure 6: Left: spectrogram (logarithmic frequency axis) of a recording in a room in the apartment. Right: Same recording with a spectrogram where the level is weighted according to the normal hearing threshold (ISO 389-7:2005).

In Figure 6 right, the same recording is shown with a threshold-weighted spectrogram, which gives a rough estimation of the audibility of the different frequency components. It is evident, that the frequency content below the tone is inaudible, while some of the higher harmonics above are also audible, but not as much as the 47-48 Hz component.

A third-octave-band analysis can be seen in Figure 7, and the  $L_{pA,LF}$  is 33.4 dB, which is considerably above the Danish limits of 25 dB (daytime) and 20 dB (nighttime). Spectrograms of a recording in the hallway outside the apartment can be seen in Figure 8 left. This shows the same dominating frequency component, which also shows up on the recording outside the backdoor of the restaurant (Figure 8 right). There is no doubt from these recordings that there are high levels of low-frequency noise in the dwelling and the evidence points towards the cooling compressors in the neighbouring restaurant.

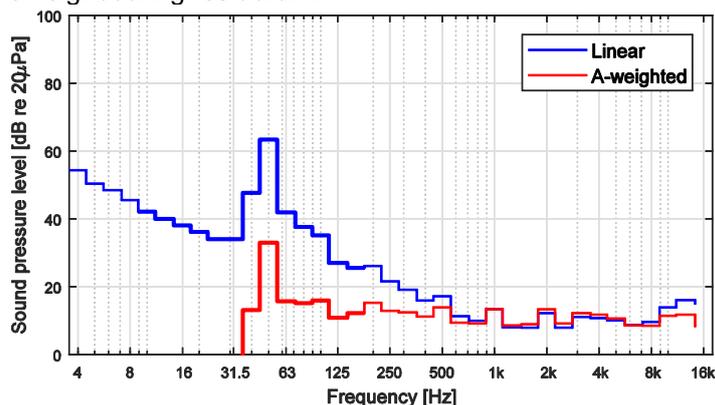


Figure 7: Third-octave-band analysis of the recording (time period 14.2-44.2 s) showing both the linear and A-weighted levels. The bold area is the 10 to 160 Hz third-octave bands used for calculating  $L_{pA,LF}$ , which for the selected period is 33.4 dB.

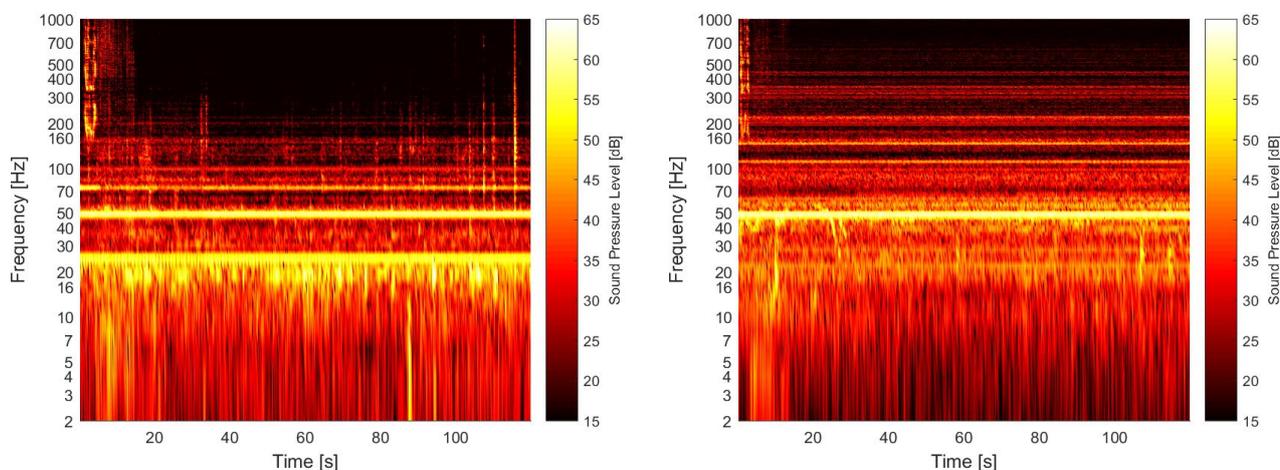


Figure 8: Left: Spectrogram of a recording in the hallway outside the apartment. Right: Spectrogram of a recording outside of the backdoor of the neighbouring restaurant.

### 3.2 Heat pump noise case

In this case, the neighbour has a heat pump placed close to the occupant's house. The occupant has used the device to make several recordings both indoor and outdoor, both at the façade and at the border between the properties. The usual problem in this case is that the noise is not stationary (see Figure 9), which means that it can be difficult to get a proper recording. Indoor recordings did not reveal any audible low-frequency noise, but rather some mid-frequency tones (see Figure 10 left). This shows that the system is also capable of assessing mid-frequency noise. Facing the occupant with this information revealed, that the problem was mainly an outdoor low-frequency noise problem, which is backed up by a number of outdoor recordings that all show the fundamental frequency (48 Hz) (see Figure 10 right) of the higher harmonics seen in the indoor recordings. This is an example of communications problems that are also part of the challenges of assessment of noise.

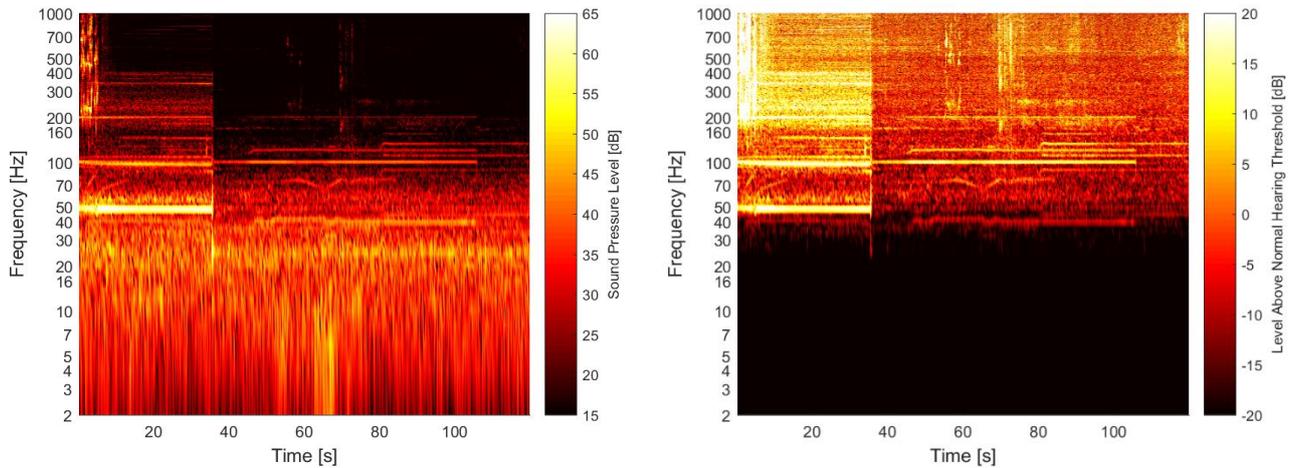


Figure 9: Left: Spectrogram of an outdoor recording. Right: a threshold-weighted spectrogram of the same recording.

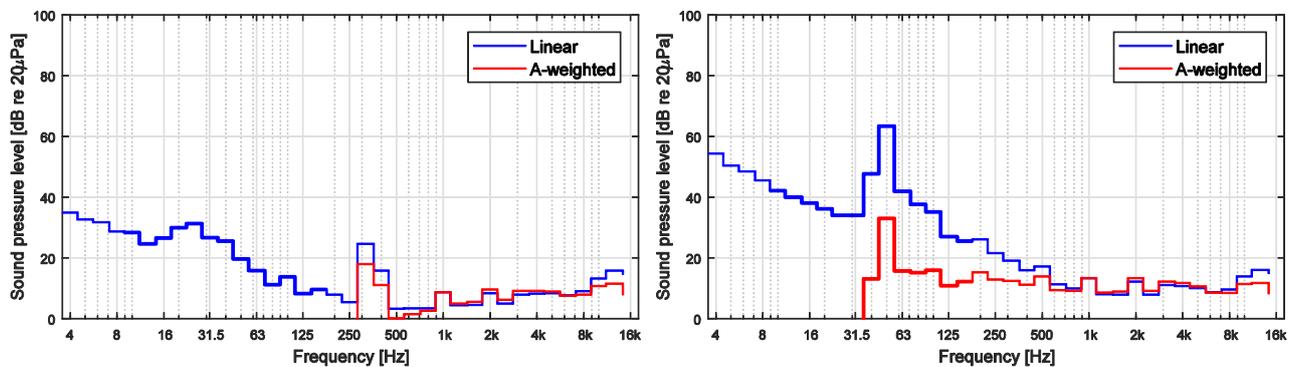


Figure 10: Left: Third-octave-band analysis of indoor recording ( $L_{pA,LF} = 1.4$  dB). Right: Third-octave-band analysis of an outdoor recording ( $L_{pA,LF} = 37.4$  dB).

### 3.3 Wind turbine noise case

The occupant suspects nearby wind turbines to be the source of low-frequency noise in the dwelling. The occupant has made recordings at different times of the day and in different positions. Both indoor, outdoor and closer to the wind turbine outdoor.

Figure 11 shows a spectrogram (left) and a threshold-weighted spectrogram (right) of an indoor recording in the living room. The dominating low-frequency noise component is an approx. 68 Hz tonal component and higher harmonics that vary in level. Overall the  $L_{pA,LF}$  is 26.0 dB (see Figure 12 left), which is above the Danish low-frequency noise limits. Figure 12 right shows an outdoor recording made approx. an hour later at a position 190 m from the nearest wind turbine, and the same tonal components are found. It is seen that the noise varies with time, which is typical for wind turbine noise as the wind direction, wind speed profile and inflow turbulence change over time. These measurements are supported by the official measurement report on the wind turbines, which also show a 68 Hz tone from the nearest wind turbine, which is more pronounced at higher wind speeds.

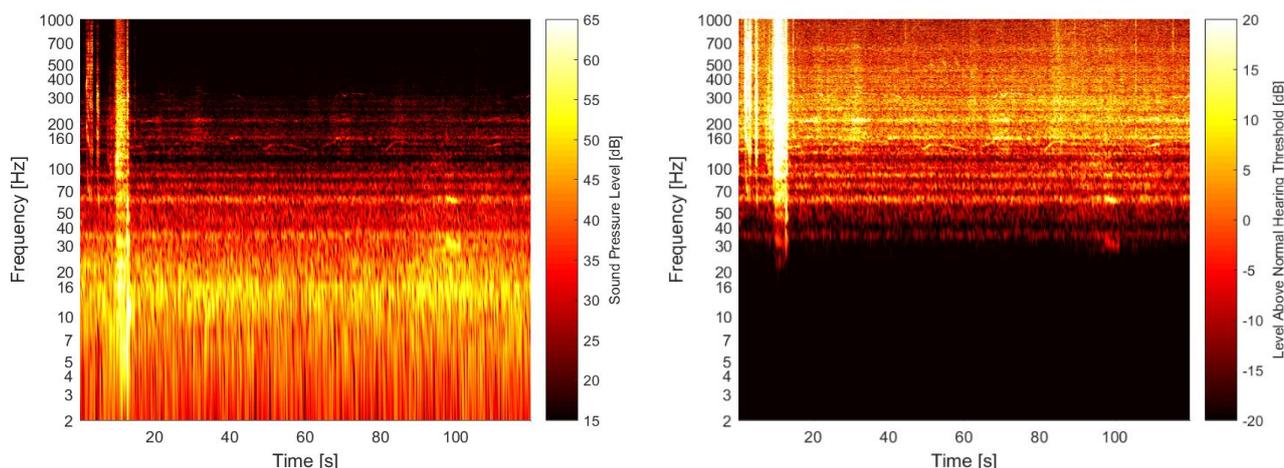


Figure 11: Left: Spectrogram of a recording in the living room. Right: Threshold-weighted spectrogram of the same recording.

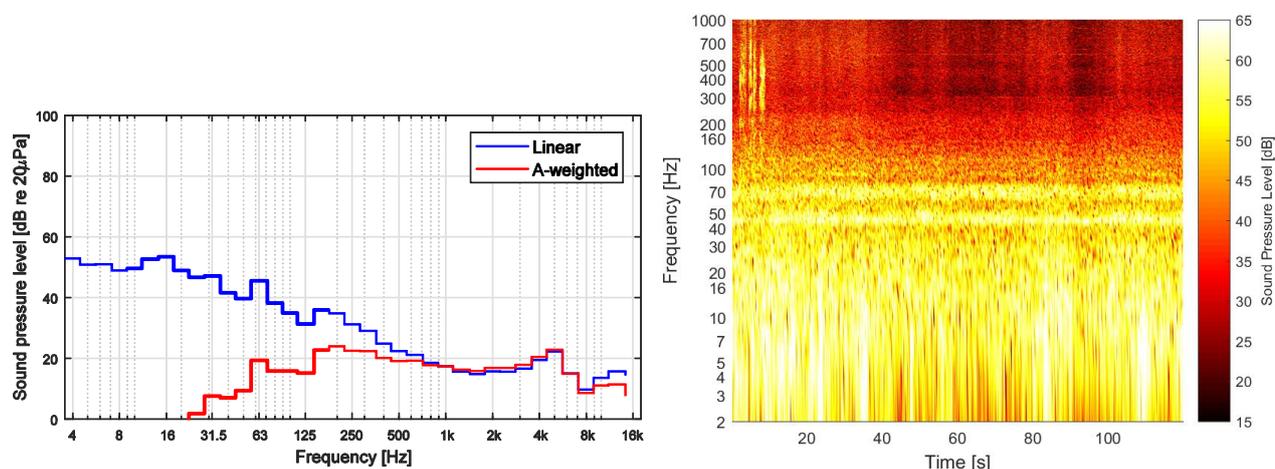


Figure 12: Left: Third-octave-band analysis of the indoor recording (time period 16.7-120 s) ( $L_{pA,LF} = 26.0$  dB). Right: Spectrogram of an outdoor measurement 190 m from the nearest wind turbine.

#### 4 DISCUSSION

As mentioned in section 1.1 standing waves cause the SPL to vary considerably with position in the dwelling. The variation is most distinct with pure tones (Pedersen, Møller, and Persson-Waye 2007), so how is this applicable to the real cases?

All three of the shown examples have tonal components, and experience from other cases e.g. (Pedersen, Møller, and Waye 2008) shows predominantly low-frequency tonal components. This means that there will be considerable pressure variation inside the dwellings and the position of the microphone is crucial for getting representative measurements. The occupant is advised to use their ears and informed that the microphone position is very important, because the sound level can change dramatically over relatively short distances. Furthermore, the LED-meter shows the low-frequency component of the noise, and can help the occupant to find areas of high levels of low-frequency noise, thereby reducing the risk of placing the microphone at a dip of the standing waves of the dominating frequency components. However, the occupants are laymen, and even when the guidelines provided with device warn about the implications of standing waves, it may still pose a problem in the use of the device.

Measuring intermittent and time varying noise like in the heat-pump or wind turbine case can be problematic, as the occupant is instructed to leave the room during recording, which means that they may not be aware if the noise changes character or disappears during the recording. With the device, there is no way for the occupant to evaluate the recording afterwards e.g. by listening to it, so they will not be able to assess the quality of the recording. Therefore, it is important that the occupant is clearly instructed to notice any change in the noise during the recording if possible. For example, if the noise is not there, when they enter the room again after two minutes, they should make a new recording in the same position when the noise appears again. In addition,

they should also record the noise in several positions within the same room to minimize the risk of "missing" the noise.

Communication with the occupant that use of the device is important. This is exemplified in the heat pump noise case, where we wondered why the analysis of the indoor recordings show so little low-frequency noise. Talking to the occupant right after the analysis revealed that it was mostly an outdoor low-frequency noise problem.

The device has been used by occupants over the last three years, and repeated calibrations show good stability of the sensitivity and frequency response of the microphone. Figure 4 shows the result of four different calibrations over a time period from 2014-2017. The measurements are considered valid below 2 kHz, while at higher frequencies the volume in the calibrator is not a pressure field and small differences in placement will give different results. The tiny variations seen in the frequency range below 2 kHz are in fractions of a dB and can be attributed to either variation in the calibration setup, i.e. calibrator frequency response or actual variation in the microphone frequency response.

The device is used by laymen and cannot replace the need for experts for solving low-frequency noise problems, but it serves as a great tool to get extensive knowledge of the low-frequency noise components and possible identification of the noise source before doing careful measurements on site by the expert. This is especially true for time varying noise sources like wind turbines, where the noise may be prominent under certain conditions, like during night time.

## 5 CONCLUSIONS

There are several challenges in measuring low-frequency noise in dwellings, and as an attempt to solve these, a low-frequency measurement device was developed. Its ease of operation makes it possible for the occupants themselves to carry out measurements without making mistakes, and by uploading noise recordings, it is possible to analyze the low-frequency noise and possibly identify the noise source before trying to solve a case. Experiences from cases shows that the occupants are able to use the device for finding low-frequency noise in their dwellings and three of these cases were presented. Close collaboration and communication with the occupants proved important for sorting out misunderstandings.

## ACKNOWLEDGEMENTS

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