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Quantification of amplitude modulation of wind turbine emissions from acoustic and ground motion recordings

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Abstract – Amplitude modulation (AM) is a common phenomenon associated with wind turbine (WT) related noise annoyance. Within the interdisciplinary project Inter-Wind, acoustic, ground motion, and meteorological data are captured to be evaluated with noise reports of residents living near a wind farm in Southern Germany. The recorded data builds a solid data base for the evaluation of AM. The occurrence of AM is detected within acoustic and ground motion data and set in relation to all available data, including WT operational parameters, meteorology, and noise reports. In this study, the origins of detected AM are tones at 57.8 Hz and 133 Hz, related to the generator and drive train, which are amplitude modulated by the blade passing frequency. AM detection was successful both with acoustic as well as ground motion data. A comparison of a method for AM detection developed by the Institute of Acoustics (IOA reference method) with a method specifically developed to detect AM in ground motion data showed that the reference method detected AM three to six times more often than the newly developed method. AM occurred most likely during stable atmospheric conditions, with a positive lapse rate, and was (albeit to a small degree) more likely to be detected when residents reported higher levels of annoyance.

Keywords: Onshore wind energy, Wind turbine noise, Sound and vibrations, Amplitude modulation

1 Introduction

The number of onshore wind turbines (WTs) is increasing rapidly due to the energy transition and, therefore, the local acceptance of wind farms needs to be encouraged. The objection of residents towards WTs is an issue not to be neglected during wind farm planning. Expected WT noise in particular is a frequent argument against the erection of WTs, with a focus on low-frequency (20–200 Hz) emissions and infrasound (0–20 Hz) [1, 2].

In the frequency spectrum of WT emissions, the blade passing frequency (BPF) and higher harmonics in the infrasound range can be identified as distinct peaks above the broadband level and clearly attributed to the operation of the WT. Several studies have shown that infrasound from WTs is below the human hearing and perception threshold at residential locations in 1 km distance [3–5]. Recently, Nguyen et al. [6] confirmed that infrasound is most likely not audible to most people at distances larger than 1 km, whereas amplitude modulated WT sounds at higher frequencies may be audible to people at distances of up to 9 km from the wind farm.

Several studies indicate that amplitude modulated WT sound can increase the noise annoyance of residents. Pohl et al. [7] analysed recordings of annoying sounds made by residents of a wind farm. They found that, rather than high sound pressure levels (SPL), these annoying sounds were characterised by amplitude modulation (AM). Schmitter et al. [8] found that WT noise annoyance of residents of five wind farms corresponded to the occurrence of AM. In listening experiments WT sounds with AM were rated as more annoying than without [8–11]. In general, AM is the periodic variation in the amplitude of a carrier signal, i.e., a noise or vibration signal, with the amplitude of a modulating signal. Figure 1 shows an example, a carrier signal of frequency 57.8 Hz is modulated at a frequency of 0.625 Hz. The amplitude of the time signal varies within 1.6 s according to the modulation frequency of 0.625 Hz and in the frequency spectrum, the carrier tone has side peaks spaced at the modulation frequency.

Amplitude modulated WT sound can then be defined as the change in the level of audible WT sound over time.

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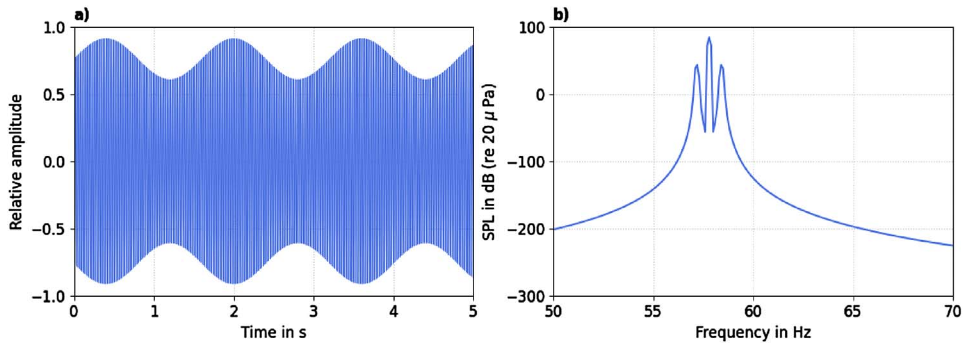

Figure 1. AM signal for carrier tone of frequency 57.8 Hz and modulating tone of frequency 0.625 Hz, (a) over time and (b) over frequency with side peaks spaced at 0.625 Hz.

The fluctuation of the sound is related to the BPF as the modulating signal [12]. For modern WTs, the BPF ranges between 0.5 Hz and 1 Hz, resulting in a pulse every 1–2 s. In the vicinity of a WT, AM is perceived as a swishing sound [13]. This is due to the sound emission of the trailing edge of the blades and occurs mainly in the frequency range of 400 Hz to 1 kHz. However, due to geometrical spreading and attenuation in the medium (air and ground) over distance, the remaining noise at the point of immission can be masked by background noise [13, 14]. At larger distances (>1 km) from the WT, in the vicinity of residential buildings, the low frequencies dominate and the noise is more likely to be described as thumping [15]. Beside aerodynamic sound being amplitude modulated, there is also the chance, that mechanic noise from the drive train might be involved [16]. Especially gearbox vibrations can be a source of AM and vibration measurements within the WT are implemented for condition monitoring (e.g., [17–19]). Vibrations of the WTs are also detectable at residential locations, although amplitudes are below perception thresholds [4]. Therefore, also ground motion recordings may be suitable to detect the occurrence of AM.

Several investigations conclude that the occurrence of AM and the AM depth, which is the peak to trough variation of the SPL time-series, are highly related to meteorological conditions during sound propagation. Paulraj and Välisuo [20], Hansen et al. [15], Conrady et al. [21], Janhunen et al. [22] found relations to wind direction depending on the position of the recording devices relative to the WTs, where AM occurrence and AM depth is higher for cross- and downwind sectors. In addition, the number of AM occurrences increases with wind speeds up to a certain value and then declines [20]. AM occurs more often during stable atmospheric conditions and low solar elevation angles (indicating late evening, night and early morning hours) corresponding to temperature inversions and clear nights [21, 23].

So far, there is no standard procedure for quantifying AM and determining the AM depth. Many studies have proposed different methods, as different metrics may be appropriate for different situations depending on the site [24].

In the Inter-Wind project [25], acoustic and ground motion data were studied together to better understand the origin of the WT emissions and to determine their decay, especially in the ground motion signals [26]. Different measuring devices and signals with different propagation mechanisms influence the characterization of WT signals. Therefore, within this study both acoustic and ground motion data are investigated with respect to AM.

A hybrid method is typically used for identification of acoustic AM. The method was developed by the AM Working group of the UK Institute of Acoustics (IOA) and combines an analysis in the time- and frequency domain [12]. So far, AM from WTs in ground motion recordings have not been investigated. Tones related to the generator and drive train can also be measured in ground motion data in the vicinity of the wind farm. Cooper et al. [16] concluded that gearbox noise might be amplitude modulated. Therefore, AM is analysed by applying the IOA method to ground motion data as well and an additional method to quantify AM in largely unprocessed acoustic and ground motion data is proposed. Comparing the two methods and AM occurrences in both data sets can verify the frequency range chosen for the evaluation. This is especially relevant for the IOA method, where AM is first calculated for three different frequency bands and the band with the greatest AM depth is selected for further evaluation. It could allow an assessment of whether mainly one tone or several tones in a wider frequency band are amplitude modulated. One advantage of using two methods simultaneously is that one can be more certain of the presence of AM when detections are consistent between both methods. Additionally, relations to wind farm operation, meteorological parameters, infrasound occurrence, and the resident annoyance are investigated in this study.

2 Measurements and instrumentation

Measurements were carried out at wind farm Tegelberg on the Eastern Swabian Alb near Geislingen an der Steige in Southern Germany from 2022/03/23 to 2022/05/12 for 50 days (Fig. 2). As part of the Inter-Wind project, measurement campaigns were directed at quantifying

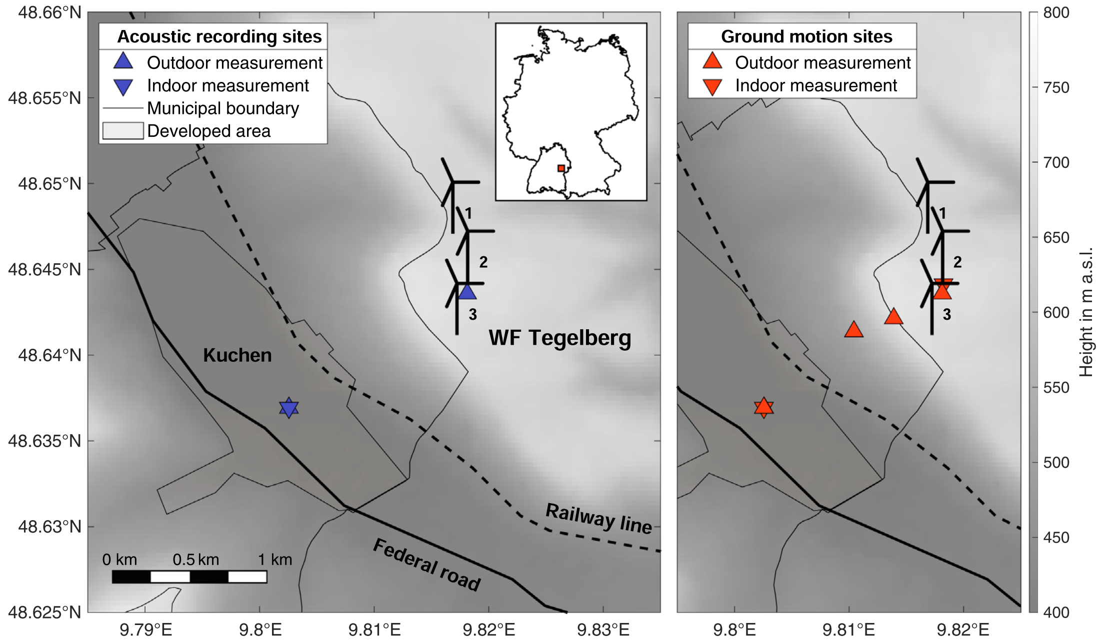

Figure 2. Topographic map of the town of Kuchen and its surroundings with locations of the WTs of wind farm Tegelberg, as well as sites with acoustic (left), and ground motion (right) recording instruments which were recording from 2022/03/23 to 2022/05/12. The inset shows the location of the measurement area (red marker) within Germany and the state of Baden-Württemberg.

acoustic and ground motion emissions from the wind farm. Additionally, meteorological data were captured and resident annoyance was documented via a noise reporting app. A first measurement campaign at wind farm Tegelberg, which consists of three WTs (Fig. 2), was conducted in 2020. All WTs (pitch controlled, type GE 2.75-120) have a hub height of 139 m, 120 m rotor diameter, 2.78 MW rated power and a rated rotational speed of 12.5 rpm. All details regarding the measurement campaign and instrumentation can be found in [25].

In the 2022 campaign, WT 3 was out of operation during the entire measurement campaign due to repair work while WT 1 and WT 2 were in operation continuously. Instruments were installed at the wind farm and in the town of Kuchen (Fig. 2). A ground motion recording instrument was placed within the tower of WT 2, and acoustic and ground motion recording equipment was installed at approximately 70 m distance south of WT 2 (Fig. 3). Here humidity was measured at a height of 5 m with a sampling rate of 10 Hz. These data are used only for data filtering in this paper. Due to the recording time of 8 weeks during the 2022 campaign, no resident agreed to have measurements at their home (in 2020 four residents participated in the campaign). Instead a public swimming pool in Kuchen was used as a representative location. A clubhouse of the German lifesaving association was used for indoor measurements. Figure 4 shows the set-up schematically. The indoor microphone was positioned 1.9 m above ground. Furthermore, a microphone was placed on the lawn outside the building in 10 m distance and a ground motion recording instrument was installed near the outside wall of the building on a paved surface. For this measurement campaign, the sampling rate for ground motion measurements was set to 400 Hz for a better comparability with the low-frequency acoustic data.

Residents of the wind farm (n = 58) were provided an app that allowed them to log their noise perceptions [25]. They were asked to make a report every evening before they went to bed – independent of whether they experienced noise in that moment or not – and, additionally, at any other time when they heard noise. In the app they stated if they heard WT sounds and were asked to rate the level of noise annoyance on a scale from 0 “not at all” to 4 “very”. It was recorded at what time they used the app, and what time they were referring to, if they described a situation with a different time than the one of app usage. Usage of the app was voluntary, participants did not receive financial compensation for their reports. It was activated simultaneously to acoustic, ground motion and meteorological measurements, allowing an analysis of the logged noise situations. In order to ensure accuracy, noise reports were filtered so that the time of the described situations did not differ more than 2 hours from the time of app usage. Between 2022/04/07 and 2022/05/11, 189 noise reports by 17 residents were considered. These residents were predominantly male (82.4%) with an average age of 63 years (range 41–79 years). The average distance of their dwelling to the closest WT was 1440 m (range 970–2120 m). None of the participants received any financial benefits from the wind farm or was working in the wind energy industry.

Meteorological data were measured at a meteorological mast at the WINSENT test site 2.4 km north-east of the wind farm [25]. In this paper, mostly meteorological data from that mast were used [27]; wind speed and direction were taken from the Supervisory Control and Data Acquisition (SCADA) data of wind farm Tegelberg. [25] showed

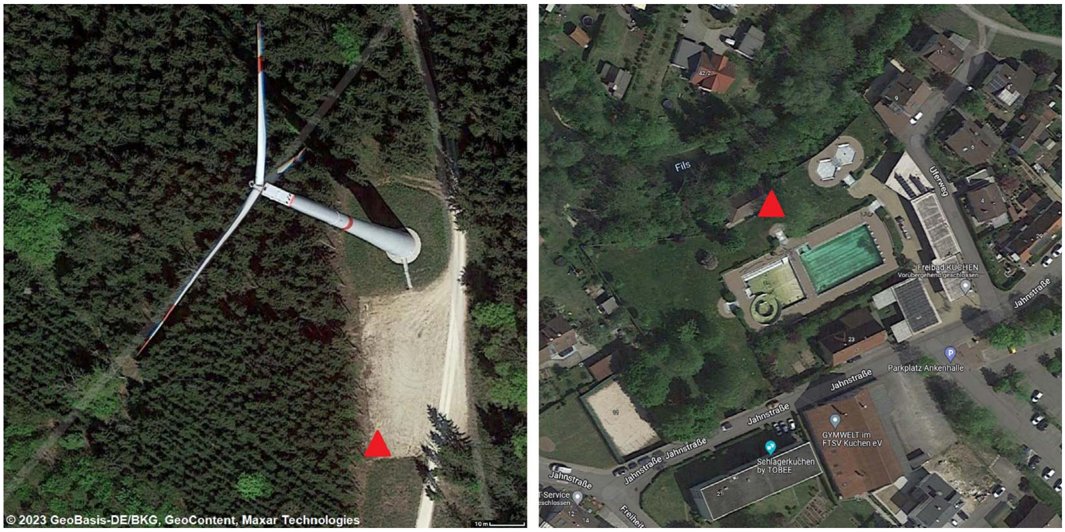

Figure 3. Detailed maps of the measurement locations at WT 2 of wind farm Tegelberg (left) and the public swimming pool at the town of Kuchen (right). Source: maps.google.de (accessed 2022/12/06).

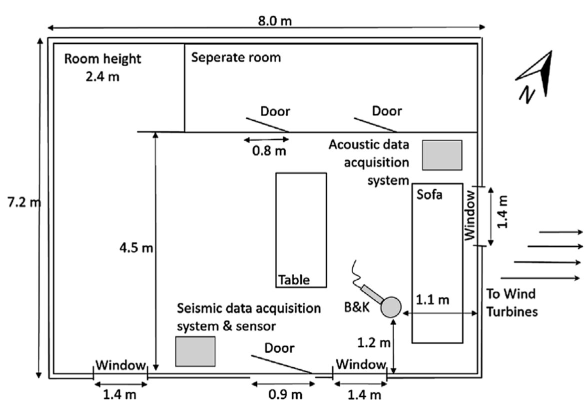

Figure 4. Sketch showing the instrumentation set-up inside the building. Exterior facades are marked with a double line.

that meteorological parameters, like wind speed and temperature, are well transferable from the test site to wind farm Tegelberg. The transferability is used for matching the acoustic measurement data with atmospheric stability parameters in Section 4.3. In Figure 5 all considered meteorological and WT-operating data are shown for the 2 week time period from 2022/04/16 to 2022/04/29.

To assess atmospheric stability, the lapse rate γ is calculated, which describes the static stability of the atmospheric boundary layer. γ is based on the gradient of virtual potential temperature Θ_v [31] at two different heights z, corrected for air pressure, moisture and density effects and is defined as

$$\gamma = \frac{\Delta \Theta_v}{\Delta z}. \tag{1}$$

This parameter only considers buoyancy effects and no mixing within the atmosphere, such as the Richardson number or the Monin–Obukhov stability parameter. However, this parameter provides robust results and is therefore suitable for a larger study area, as described in Platis et al. [28]. This is necessary for the comparison of sound and ground motion data in the valley location (1 km distance from the wind farm) with stability measurements (2.4 km distance from the wind farm) at a distance of approximately 3.4 km. Parameters that consider turbulence depend on local conditions such as vegetation and topography and are therefore less robust in a larger area.

In this work, γ (with the unit Kelvin per meter) is calculated using the temperatures at 3 m and 97 m height at the meteorological mast and divided into classes according to Table 1. Temperature data and atmospheric stability according to the lapse rate are shown in Figure 5a. With positive γ values, the temperature increases with height by the given value. It indicates little mixing of the air layers, hence stable atmospheric conditions, whereas negative values indicate unstable atmospheric conditions [28, 29].

For the calculation of the wind speed difference, wind speeds at heights of 11 m and 98 m were used. Figure 5b shows that higher wind speed differences are measured especially at night, which means that lower wind speeds are present at ground level compared to higher altitudes. Here the wind speed difference is defined by

$$\Delta v = v_{98m} - v_{11m} \tag{2}$$

where v_{98m} is the wind speed in 98 m height and v_{11m} in 11 m height of the meteorological mast. Rain intensity measurements can be used to identify periods of rain. In addition, the humidity (Fig. 5c) provides information about humid weather conditions such as fog. From the air pressure measurements one can see that the pressure shortly drops before a rain event.

Figure 5d shows operational data from WT 2. During the two weeks, the wind came mainly from eastern direction, with the main wind direction during the year typically being north-west [25]. Therefore the microphone at the wind farm had a crosswind and the microphone at the

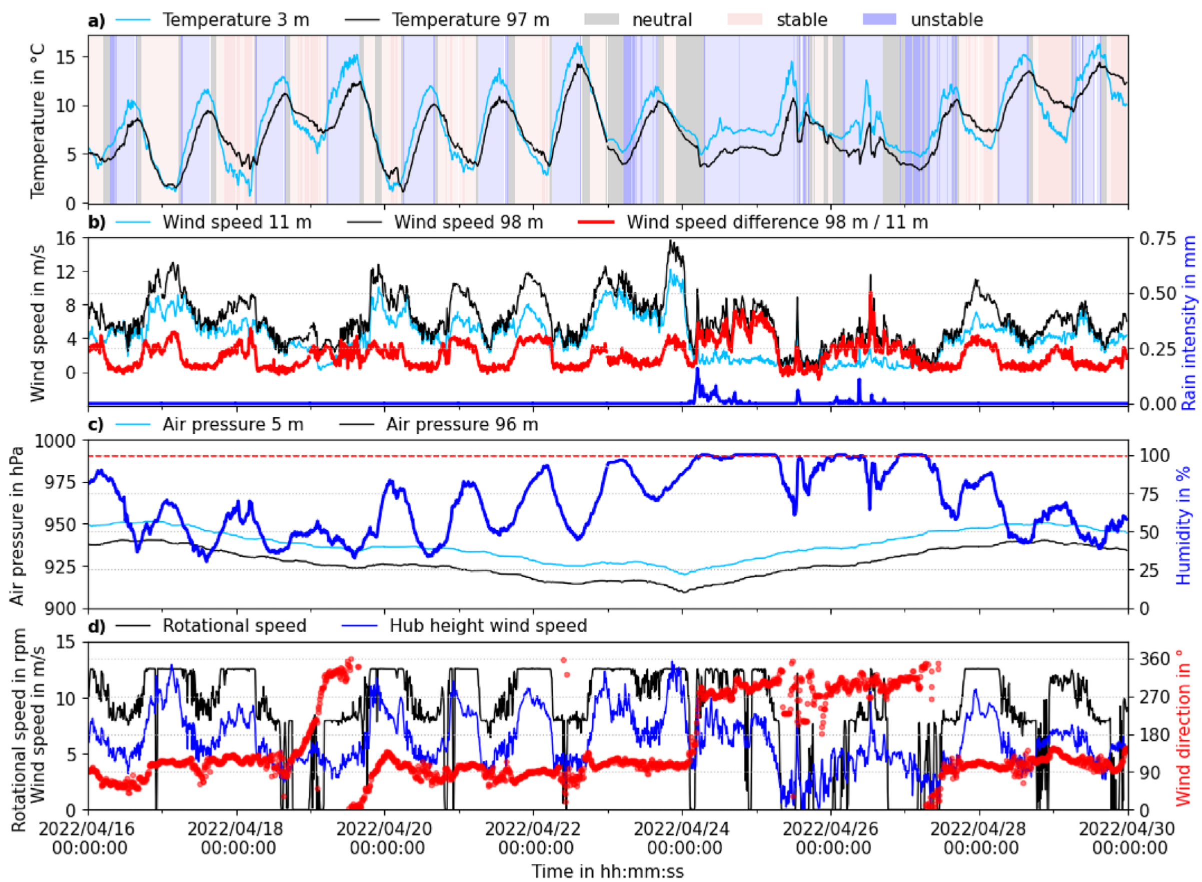

Figure 5. Data for the measurement campaign from 2022/04/16 to 2022/04/29. (a) Temperature at 3 m and 96 m height and lapse rate γ, colour coded according to Table 1, indicating stable, neutral or unstable atmospheric conditions. (b) Wind speed at 3 m and 98 m height. (c) Air pressure at 5 m and 96 m height and humidity at 3 m height, the red line indicates the filter limit at 99% for AM exclusion. (d) Rotational speed, wind speed and wind direction at hub height of WT 2. (a)–(c) were measured at the WINSENT test site.

Table 1. Overview of stability classification for the lapse rate γ, calculated between highest (97 m) and lowest (3 m) level of the meteorological mast.

Stability classification	γ class	Range in Kelvin/100 m
	−3	$\gamma \leq -0{,}9$
Unstable	−2	$-0{,}9 < \gamma \leq -0{,}7$
	−1	$-0{,}7 < \gamma \leq -0{,}5$
Neutral	0	$-0{,}5 < \gamma \leq -1{,}5$
	1	$-1{,}5 < \gamma \leq 2{,}5$
Stable	2	$2{,}5 < \gamma \leq 5$
	3	$5 < \gamma$

building a cross-/downwind orientation relative to WT 2. Wind speeds measured at hub height of the WT are similar to those measured at the meteorological mast on the test site. Higher wind speeds mean higher rotational speed of the WT, which are mainly observed during the night.

For the joint investigation of AM in the ground motion and acoustic data, a period of two weeks from 2022/04/16 to 2022/04/29 was chosen. The ground motion instrument near the WT had been installed on 2022/04/13. Furthermore, for the comparison of acoustic AM with meteorological parameters and infrasound, the entire measurement campaign is considered (see Tab. 2).

3 Detection and quantification of AM

In the following, AM is detected in both acoustic and ground motion data (Fig. 6) with two different methods. The detection of AM in acoustic data is based on the method of the Amplitude Modulation Working Group of the Institute of Acoustics [12] and is called the *IOA reference method* in the following. This method is applied to both data sets. Furthermore a newly developed method is proposed, quantifying the side peak prominence (SPP) for the 57.8 Hz tone in the raw, unprocessed data. This tone is related to the 2nd harmonic of the fundamental generator speed frequency of 28.3 Hz, as the generator speed data is available from the wind farm operator, and occurs at the rated rotational speed of 12.5 rpm.

Thus, AM is only detected at rated rotational speed with the SPP method. The relation between BPF and frequency of signals related to the generator and the drive

Table 2. Time periods for data evaluation.

Sections 4.1 and 4.2: AM in acoustic and ground motion data	2022/04/16	2022/04/29
Sections 4.3 and 4.4: AM related to meteorology and infrasound	2022/03/24	2022/05/11
Section 4.5: AM related to annoyance	2022/04/07	2022/05/11

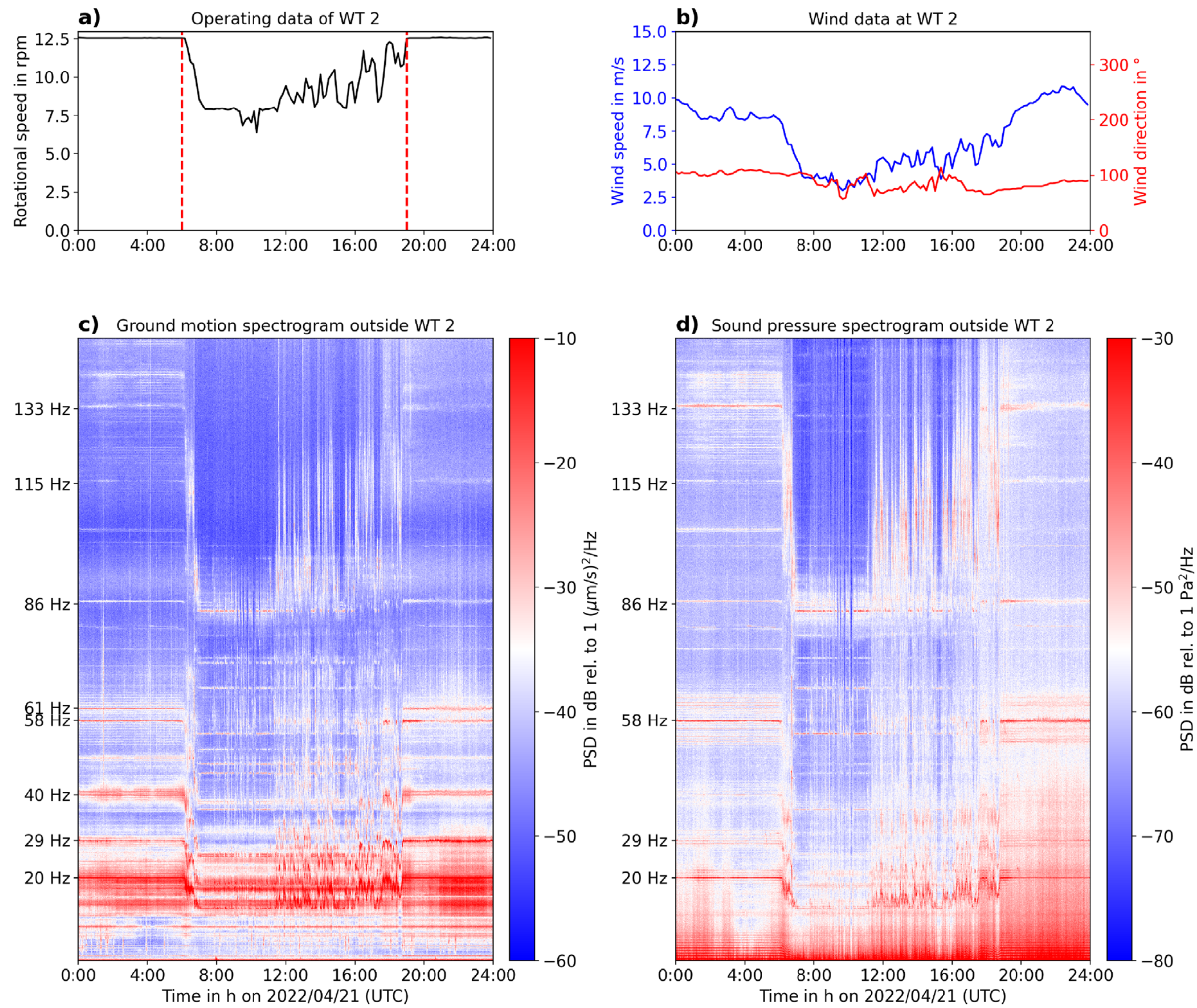

Figure 6. Operating and wind data of WT 2 for 2022/04/21 with the respective ground motion and acoustic spectrograms for frequencies up to 150 Hz showing the presence of AM of multiple tones, which can be identified by horizontal lines around the carrier tones (57.8 Hz and 133 Hz) spaced at the BPF. The red-dashed lines in (a) indicate the end and start of the time windows used for the spectra shown in Figure 10. (a) Operating data of WT 2, (b) wind data of WT 2, (c) ground motion spectrogram outside WT 2 and (d) sound pressure spectrogram WT 2.

train of the WT are listed in Table 3. Both methods are applied to each data set and the results are compared in Section 4.1.

3.1 AM detection with the IOA method

Here, AM detection using the IOA reference method is demonstrated with the use of acoustic data. This method was used in its original version by Paulraj and Välisuo [20], Jennings and Kennedy [30], but also in an adapted form by Hansen et al. [15]. In addition, the method has already been used in a research field other than wind energy, namely bird characterisation [31].

Detailed descriptions of the analysis methods can be found in Bass et al. [12], Paulraj and Välisuo [20], Hansen et al. [15], Jennings and Kennedy [30]. Based on visual inspection, different tones were identified that are amplitude modulated. Figure 7 shows a data example from the microphone positioned in 1 km distance outside the building for the day of 2022/03/26. It clearly shows a tone at

Table 3. Frequencies corresponding to signals from the drive train of the WT at rated conditions with 12.5 rpm.

Harmonic of BPF	Frequency (Hz)
32xBPF	20
46xBPF	28.75
92xBPF	57.5
214xBPF	133.75

57.8 Hz with side bands spaced at the BPF in the evening between 18:00 and 24:00 UTC and one at 133 Hz with side bands between 21:00 and 24:00 UTC. AM was calculated according to the reference method for three frequency bands, namely 50–200 Hz, 100–400 Hz and 200–800 Hz. However, at a distance of 1 km from the WT, the highest values for AM depth were calculated for the frequency band 50–200 Hz, which also contains the two identified tones. For this reason, this frequency range was selected for a more extensive evaluation.

The algorithm was applied to the data of the wind farm measurements as well as to the data at a distance of 1 km. For comparison with the ground motion data and to reduce false positive AM detections, the frequency range surrounds 0.625 Hz (0.6–0.8 Hz) which corresponds to the BPF at 12.5 rpm of the WT. The open source Python code published by the IOA for the reference method was used to detect AM and calculate AM depth [12]. As input for the analysis, the recorded 10-minute data were converted into A-weighted and bandpass filtered 100 millisecond L_{eq} values. Reference values to calculate L_{eq} were 20 μPa for acoustic and 100 μm/s for ground motion data. A flowchart in Figure 8 gives an overview of the analysis.

Figure 9 shows a comparison between the detected AM and the spectrograms at the wind farm and at the building in Kuchen over a period of 2 days. The power spectral density (PSD) of the acoustic data was calculated for a time duration of 10 s and a frequency resolution of 0.1 Hz using a Hamming window and an overlap of 50%. Both PSDs at the wind farm and at the building are shown for the frequency range around 57.8 Hz. In Figure 9c and 9d the 10-minute AM values for a frequency range of 50–200 Hz are plotted over time. The comparison of Figures 9a and 9c indicates a good agreement of detected AM at the wind farm location with the spectrogram. In the evening of 2022/03/27 AM occurrences are detected, which are not visible in the spectrogram and might be false positives. The fluctuation of the AM depth can be attributed to varying wind speeds and the associated change in pitch angle of the rotor blade. For the building at 1 km distance (shown by Figs. 9b and 9d), detected AM occurrences match the visible AM in the spectrogram.

For further evaluation, data points were excluded when the rotational speed of WT 2 was below 4 rpm, during rainfall and air humidity above 99%. For the humidity filtering, data was taken from the WIN SENT test site and from the wind farm location measurements close to the microphone. The exclusion criteria rainfall and rotational speed have already been applied in other studies [6, 23, 30]. In Schmitter et al. [8], the maximum humidity was set to 95%, which would have led to a total of 20% data exclusion, so the value was set higher. Less than 13% of the AM data were thus excluded of the entire measurement campaign and for the two week time period. Table 4 shows the percentage of AM occurrences at the wind farm and at the building location.

To estimate the uncertainty of the AM detection method, Larsson and Öhlund [23] suggest to use measurement data from a site without WTs. Therefore, data from a measurement campaign in spring 2021 outside a residential building close to the WINSENT test site was used for AM detection. Data between 2021/06/11 and 2021/07/08 was investigated. Within 3952 data points one 10-minute block was rated with valid AM. From this, an uncertainty of the AM detection of 0.02% is obtained, which demonstrates a good reliability of this method for the identification of WT-related AM. Wind speed, air pressure and humidity had similar values as in spring 2022.

3.2 AM detection with the SPP method

AM is also directly observed in spectrograms of the raw data, with more or less prominent side tones to the main signals (Fig. 6). Therefore, a method to quantify AM occurrence from the raw data is designed, as a transformation to SPL is typically not applied to ground motion data and thus a better comparability is achieved by using unprocessed (raw) data. The occurrence of the side tones can then easily be evaluated from a time-frequency representation of the data (spectrograms), which is often not the case with other AM detection methods. The main signals, which are related to the WTs drive train, are observed at the frequencies marked on the y-axis of Figure 6 and are similar in both data sets, though not completely identical. There are additional peaks at 40 Hz and 61 Hz in the ground motion data which are less clearly visible in the sound pressure data. The peak at 133 Hz is much more prominent in the acoustic than in the ground motion data. The following is focused on frequencies of up to 70 Hz for AM detection, because signals in this frequency range are much more prominent in the ground motion data.

In this section, AM is detected in spectra of 10-minute time windows, calculated for window lengths of 60 s and 20 s overlap with the PSD function of the Python toolbox matplotlib.pyplot [32]. As shown in Figure 10, the tone at 57.8 Hz is most suitable for a detection of AM by taking the prominence of the side peaks, located at distances of multiples of the BPF. Fixed frequency ranges are used to calculate the mean values of the side peak and the background amplitudes (see Fig. 11). With the resulting mean values, the side peak prominence (SPP, Fig. 12) is calculated which is then used to quantify AM in the ground motion and acoustic data. A prominence of $>$2 dB is considered as a successful AM detection, because lower SPP values occur for all rotational speeds and would, therefore, not be reasonable. At sites further away than 70 m distance to WT 2 SPP values of more than 2 dB are hardly observed (Fig. 13). The method is called the *SPP method* in the following.

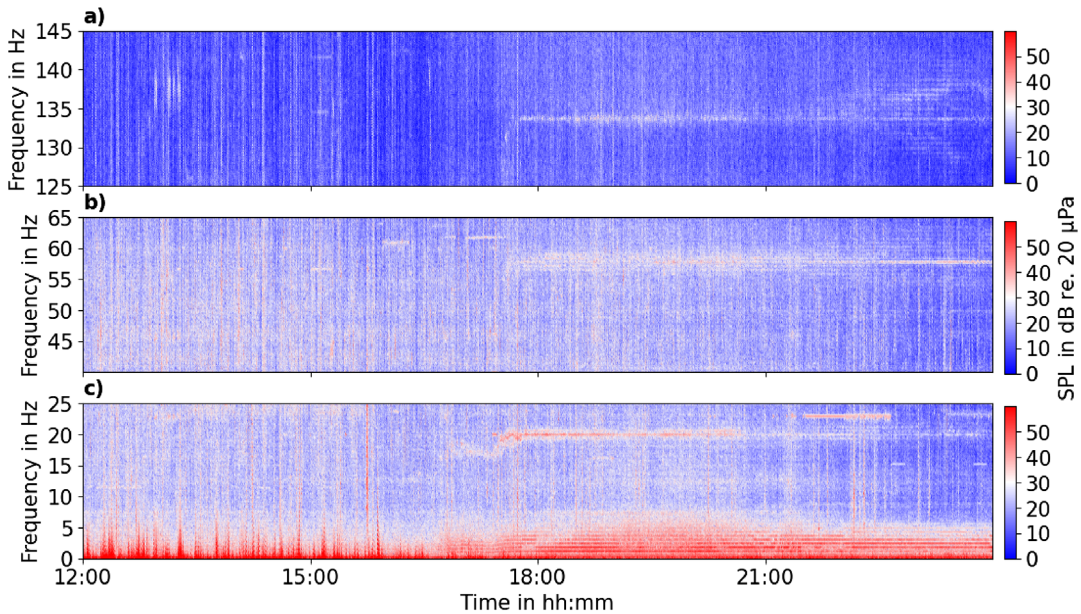

Figure 7. SPL spectrogram showing the presence of AM of multiple tones on 2022/03/26 in 1 km distance to the wind farm. AM can be identified by horizontal lines around the carrier tone (57.8 Hz and 133 Hz) spaced at the BPF (modulation frequency) in the evening hours between 18:00 and 24:00 UTC.

4 Results

Here, results are shown for the application of both methods to each of the data sets. The acoustic data set contains data for both the wind farm and the location at the building within the town of Kuchen. The ground motion data evaluated is from the wind farm only. Because the side peaks decrease in prominence with distance, the detection rate of the SPP method was too low for a comparison with data from any other ground motion measurement location. This is due to the stronger attenuation of the elastic emissions in the subsurface of the ground compared to the acoustic emissions propagating through the air and therefore reduced prominence and detectability. Due to the later installation of the ground motion instrument at the wind farm, different time periods are taken for the following evaluations (see Tab. 2). Furthermore, the resident survey started only at 2022/04/07 for which AM detection is analysed in Section 4.5.

4.1 AM in acoustic and ground motion data

For the comparison of AM in acoustic and ground motion data, the two different approaches of the IOA and SPP methods are applied. The resulting AM depth and SPP for each 10-minute time window are shown for 2 weeks in Figure 14. For this time period, 32% of the time WT 2 was running at rotational speeds above 12 rpm.

Acoustic data from the wind farm and building location within the town are evaluated as well as the ground motion data from the wind farm. For both methods, results for the ground motion and acoustic data from the wind farm are very similar in occurrence. While AM is detected more frequently during rated operation (9 nights in total) with the IOA reference method, the SPP method only finds AM occurrences during 5 nights within the 2 week period. For the location at the building, AM depth calculated with the IOA reference method is similar as for the wind farm location, but with much lower occurrence. With the SPP method there are fewer occurrences as well as reduced SPP for the building location compared to the wind farm data.

The percentages of AM detections with the IOA and the SPP method are listed in Table 5. AM is detected 3–6 times more often by the IOA method compared to the SPP Method. Figure 15 shows the percentage of AM occurrences detected with the two methods, separated into detections with one method only or both methods simultaneously. It shows that most detections are found by the IOA method and a smaller amount of detections are consistent for both methods. The least amount of detections are found by the SPP method only. For the building location the overlap of detections is lowest.

To see if there is any relation between SPP and AM depth estimated by the IOA reference method, both measures are plotted against each other (Fig. 16). It can be seen that valid AM detections with the SPP method are only found for AM depths from 2 dB to 5 dB of the IOA reference method. There is no visible correlation of the two measures (SPP and AM depth). For greater AM depths, such as on 2022/04/19 or 2022/04/23, no AM is detected with the SPP method.

For non-detections AM depth or SPP are set to 0 dB.

4.2 AM in relation to WT operation

Figure 17 presents the distribution of AM detections for the acoustic and ground motion data in relation to the wind

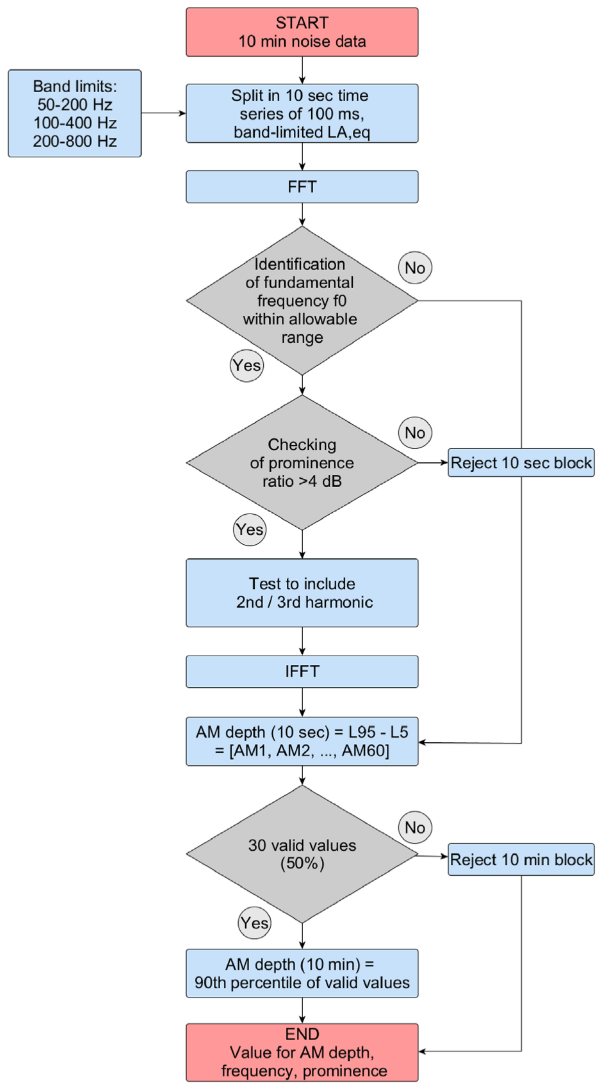

Figure 8. Flowchart for detection of AM with the IOA reference method.

speed and wind direction as captured by the sensors at WT 2. Results for the IOA reference method show a spread of valid AM detections for wind speeds above 5 m/s with increasing AM depth for wind speeds larger than 10 m/s. Valid detections cover a wind direction range of 50° (NE) to 150° (SE) with maximum AM depth at 110°, corresponding to south-eastern crosswind direction relative to the building. Results for the SPP method are more limited, to wind speeds of 7 m/s to 10.5 m/s, as the side peaks could be masked at higher wind speeds, and wind directions of 90°–135°.

As an example, in Figure 6 it can be seen that in the time window in the evening of 2022/04/21 no AM is detected with the SPP method compared to the time window in the night and early morning. Nevertheless, with the IOA method AM is detected in both time windows (Fig. 14). In the night and early morning, higher wind speeds were present than in the evening.

4.3 AM in relation to meteorological conditions

To determine if AM occurrence depends on the meteorological parameters, AM data detected with the IOA method in the acoustic data measured at the building location for the full measurement campaign (see Tab. 4) are used. In order to establish a correlation between meteorological parameters and AM, the occurrence of AM was normalised to the amount of all values of a category (e.g., stable conditions) of the entire measurement campaign.

Figure 18a shows the percentage of AM occurrence in relation to the lapse rate for a classification of unstable, neutral and stable atmospheric conditions (see Fig. 5). AM was detected during 16% of the time with stable conditions (positive lapse rate) in the measurement period. During unstable conditions, AM was present during only 0.5% of the time. This confirms a similar finding by Larsson and Öhlund [23]. Furthermore they found that AM occurs more often at the point of immission when there is a large difference in wind speed between two heights. There is also a relation between the occurrence of AM and a large difference in wind speeds between 98 m and 11 m in this study, as seen in Figure 18b, where AM occurred during 24% of the time with wind speed difference >2 m/s.

No direct relationship can be found with regard to air humidity (Fig. 18c). According to Figure 18d, AM mainly occurred at temperatures between 0 °C and 5 °C during this period, which was the main temperature range of this measurement campaign.

Lapse rate and wind speed difference seem to have an influence on the occurrence of AM in the valley location around Kuchen. This might be explained by a downward diffraction of the sound waves due to lower temperature and wind speed in lower heights [23]. According to Larsson and Öhlund [23], AM occurs more often during morning, evening and night time, which is related to the solar elevation angle, as there is a relation between lapse rate and time of day.

To classify these results, AM occurrence at the building location is related to the operational parameters of WT 2. Wind direction was divided into 4 sectors, with a downwind sector for 22°–67°, a south-east crosswind sector (cross-se) for 112°–157°, a up wind sector for 202°–247° and a north-west crosswind sector (cross-nw) for 292°–337°. Figure 19a shows, that AM mainly occurred during rated WT operation with rotational speeds above 12 rpm. During the considered two months, AM is most common for the cross-se sector and occurs with similar slightly lower percentage for the downwind sector (Fig. 19b).

Concerning wind directions, Paulraj and Välisuo [20], Jennings and Kennedy [30], Conrady et al. [21] also found highest AM occurrences during crosswind sectors. In Larsson and Öhlund [23] and Nguyen et al. [33], AM is rarely detected for upwind direction. In these studies, different relations of AM to wind direction are found. Therefore, a generally valid statement with respect to wind direction seems difficult. Furthermore, AM occurrence at the point of immission can be related to high wind speeds above 7 m/s at hub height (Fig. 19c). Although the highest

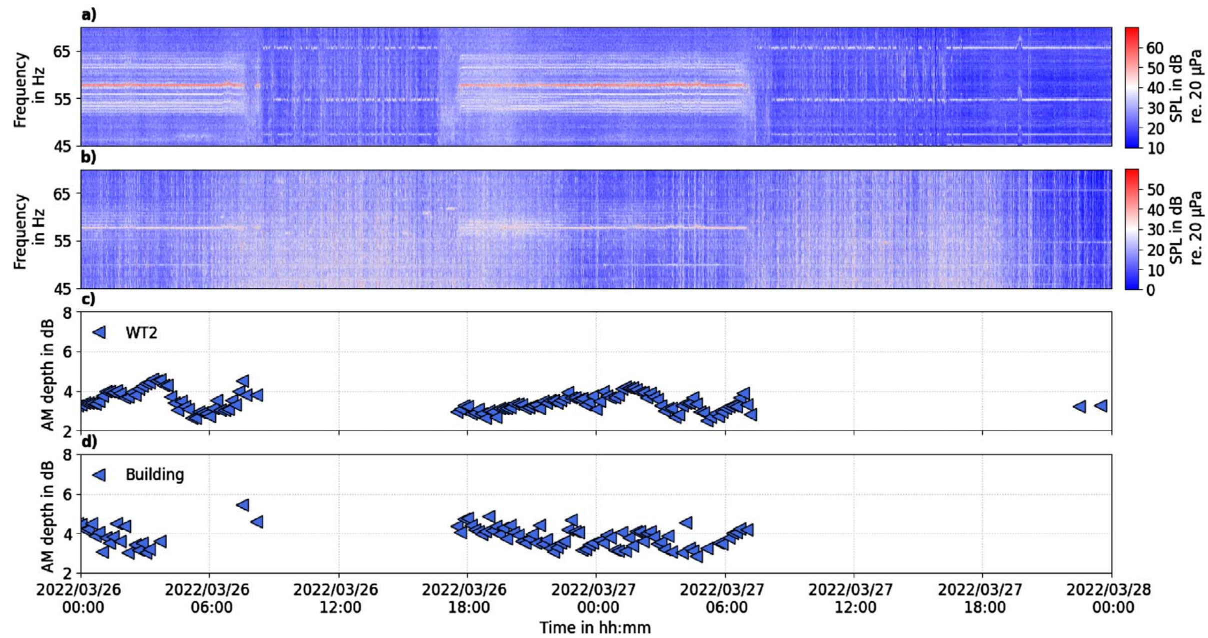

Figure 9. SPL spectrogram showing the presence of AM of multiple tones on 2022/03/26 and 2022/03/27. AM can be identified by horizontal lines around the carrier tone spaced at the BPF (modulation frequency). (a) Wind farm location, (b) outside the building at 1 km distance, (c) and (d) detected AM samples for rated rotational speed of WT 2 at the wind farm and building location.

Table 4. AM occurrence during the measurement campaign, using the IOA reference method for the frequency range 50–200 Hz.

Location	Wind farm	Building
2022/03/24–2022/05/11	20.1%	7.8%

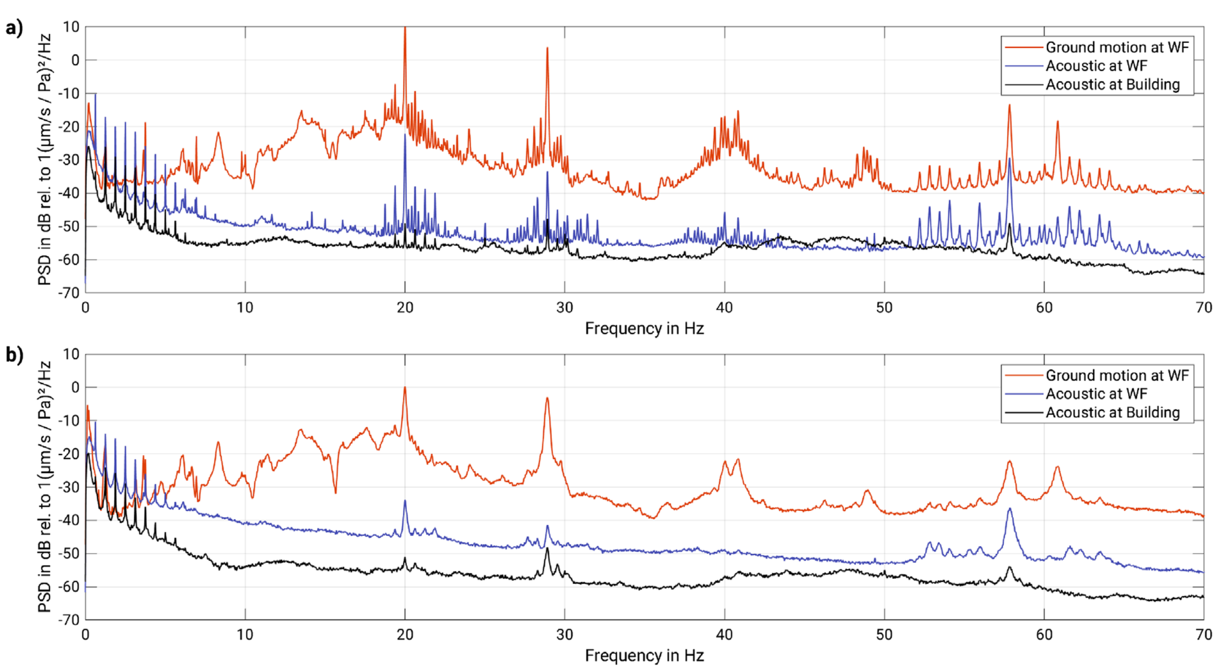

Figure 10. Spectra of acoustic and ground motion data for 2 time windows from 2022/04/21 with clear (top, 0:00–6:00 UTC) and no (bottom, 19:00–24:00 UTC) AM. While the peaks at 20 Hz and 29 Hz exhibit side peaks at distances of 1/3 of the BPF, the peak at 57.8 Hz shows side peaks at the BPF. A further main peak is observed at 61 Hz in the ground motion data, which is smaller relative to the amplitude of the surrounding frequencies in the acoustic data.

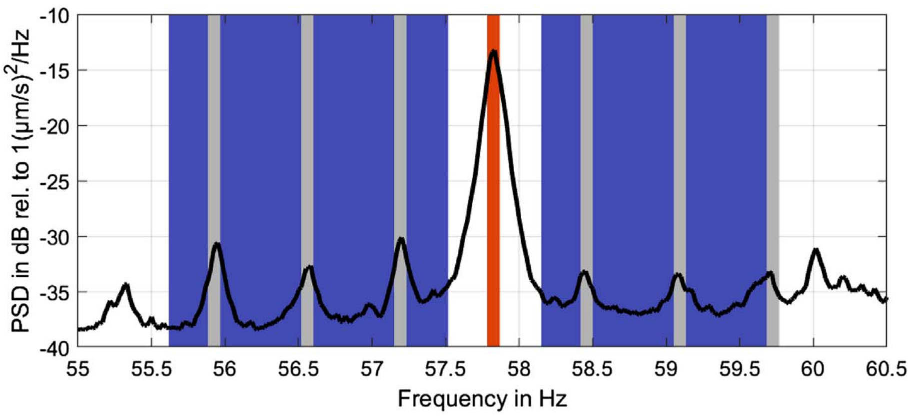

Figure 11. Ground motion spectrum centered at 57.8 Hz from 2022/04/21 0:00–6:00 UTC with clear AM. The difference of the arithmetic means of the grey and blue colored frequency areas in dB are taken to calculate the prominence of the side peaks.

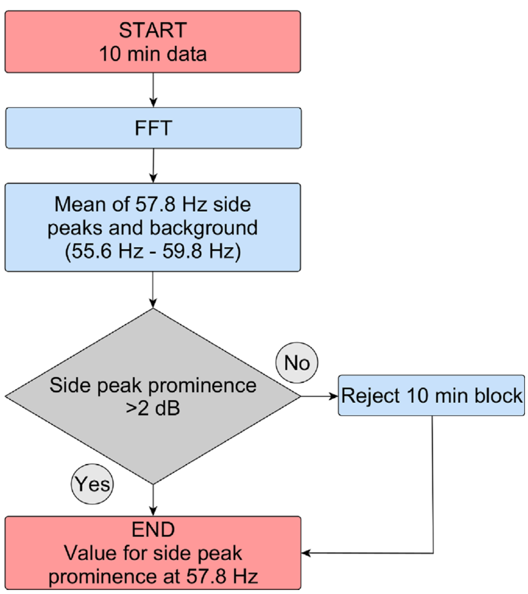

Figure 12. Flowchart for the side peak prominence (SPP) method.

AM occurrence correlates with a power capacity of over 60%, only 13% less AM is present during lower power output (Fig. 19d). These results are consistent with Hansen et al. [15] and Nguyen et al. [33].

4.4 AM in relation to infrasound occurrence

Since AM is a periodic fluctuation related to the BPF [12, 15], occurrence of AM detected with the IOA method in the acoustic data and infrasound is investigated in this section. In Blumendeller et al. [5] infrasound occurrences were identified by detecting the 4th harmonic of the BPF. The prerequisite for a detection is a peak in the 10-minute mean narrow-band spectrum between 2 Hz and 2.5 Hz with a prominence of 6 dB above the broadband noise level. If these conditions are fulfilled, the sound pressure level of the peak is captured and an infrasound occurrence is identified in this 10-minute time period.

In Figure 20, the occurrence of infrasound and AM is divided into five different combinations. The following cases are considered: absolute occurrence of AM and infrasound at the wind farm and building, and separated into the combination of AM without infrasound occurrence, AM with infrasound occurrence and infrasound without AM occurrence. At the wind farm location (Fig. 20a) AM and infrasound occur mostly together (grey bar, 15%). At the building location (Fig. 20b) more infrasound is detected without the presence of AM (5.7%), whereby the percentage of simultaneous AM and infrasound occurrences is close (5%). AM is therefore more likely to be detected together with infrasound at the point of emission. Based on this study, infrasound might be an indicator for the occurrence of AM, both at the wind farm and at the building site.

Figures 20c and 20d show the dependence of AM and infrasound on the time of day. A whole day was divided into four time periods of 6 hours, with morning from 03:00 to 09:00 UTC, day from 09:00 to 15:00 UTC, evening from 15:00 to 21:00 UTC and night from 21:00 to 03:00 UTC. Both, at the wind farm and building location AM and infrasound are mainly detected in the nighttime period, but also in the morning and evening hours. Similar results were described by Larsson and Öhlund [23] and Nguyen et al. [33], where a higher occurrence of AM was found at solar elevation angles close to zero or negative values, i.e., for the night, morning and evening hours.

4.5 AM in relation to annoyance

Using the IOA reference method and the SPP method, both applied on the acoustic data measured outside of the building, AM signals are analyzed together with noise reports made by residents. For each noise report six 10-minute intervals are considered: the 10-minute interval which included the time of the report and the 5 preceding intervals. If AM is detected in at least one of these intervals, it was considered a noise report with AM. For AM depth the highest value (maximum) across the intervals is considered for the following analyses.

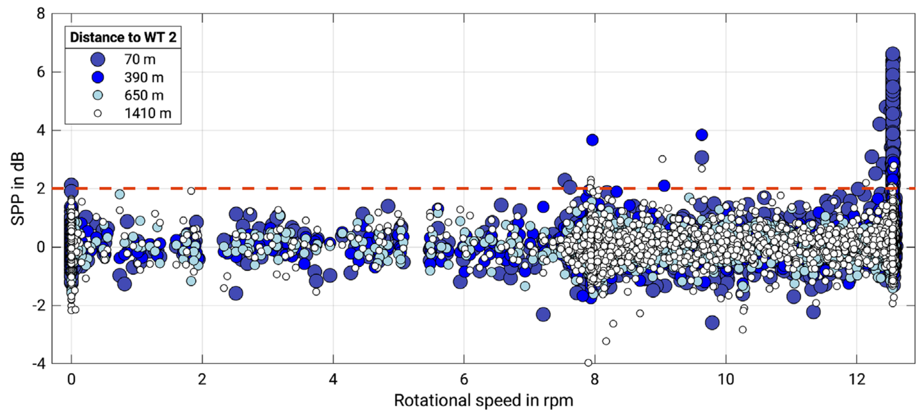

Figure 13. SPP over rotational speed for all considered 10-min time windows at the four ground motion measurement sites shown in Figure 2. The detection threshold for AM is set to 2 dB for the SPP method, indicated by the red dashed line. Lower SPP values occur for all rotational speeds and, therefore, only above this threshold detections are reasonable. Only at the site in 70 m distance to WT 2 SPP values of more than 2 dB are observed for multiple time windows.

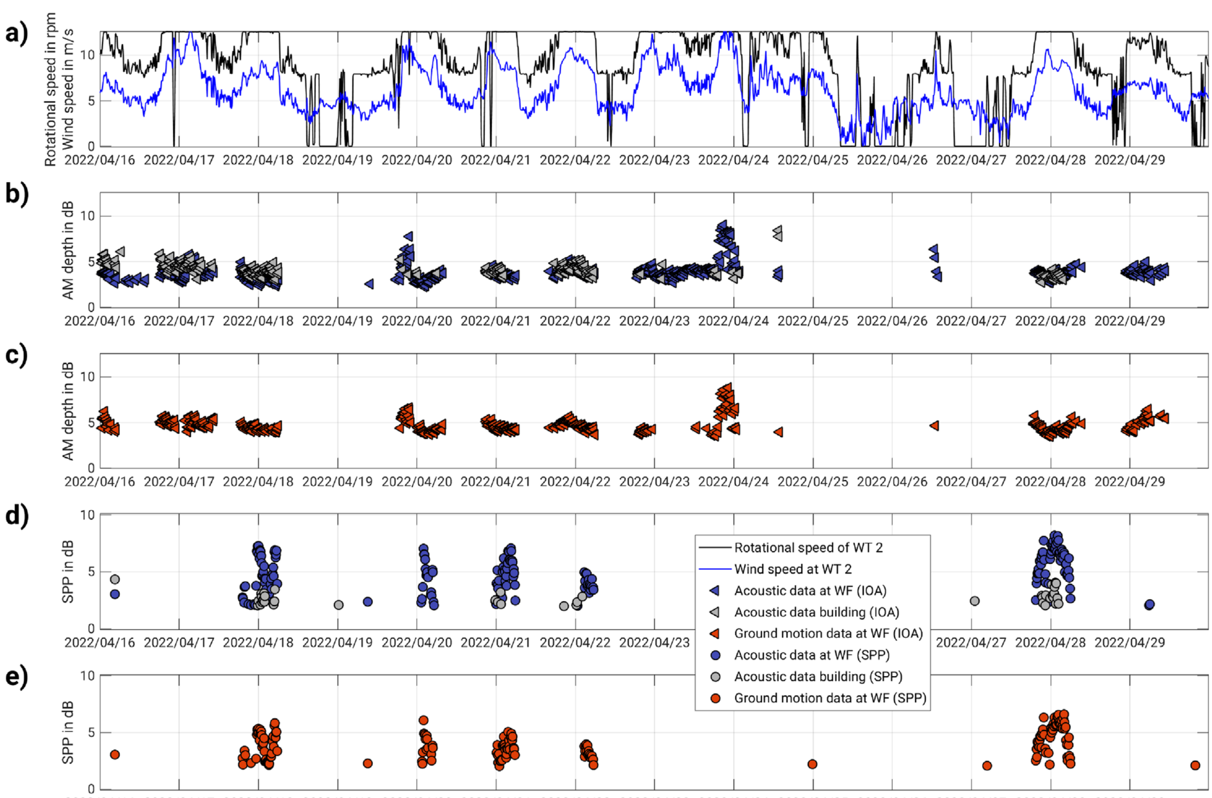

Figure 14. (a) Rotational speed and wind speed data for WT 2 of wind farm Tegelberg. (b)–(e) Results for valid AM detection from 2022/04/16 to 2022/04/29 for the (b)–(c) IOA as well as the (d)–(e) SPP methods for acoustic (blue/grey symbols) and ground motion data (red symbols).

Table 5. AM occurrence between 2022/04/16 and 2022/04/29 for all data sets and locations, using the IOA and SPP methods.

Data set	Acoustic		Ground motion
Location	Wind farm (%)	Building (%)	Wind farm (%)
IOA method	32.9	13.4	22.4
SPP method	9.1	2.1	8.4

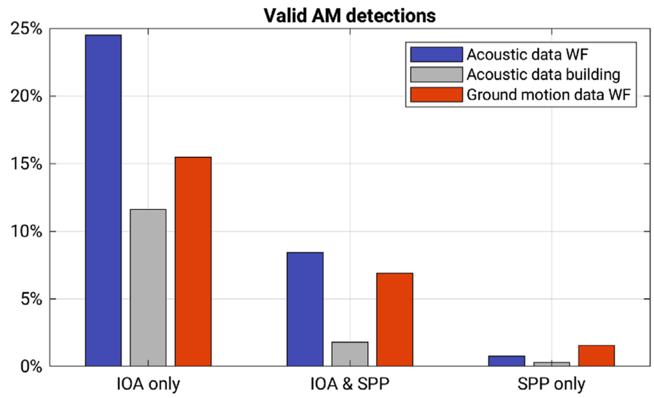

Figure 15. Comparison of AM detection results for all 10-minute time windows from 2022/04/16 to 2022/04/29. Percentage of AM detections with either the IOA or the SPP method only (left and right columns) or AM detected with both methods simultaneously (middle column). In this period, rated WT operation (rotational speed >12 rpm) was reached in 32% of the total 10-minute time windows.

Table 6 and Figure 21 display for which noise reports AM is detected. Applying the SPP method, out of 189 noise reports only three could be identified which coincided with AM. For these reports, no or a little annoyance was reported. Therefore, with regard to SPP no association with annoyance could be found. With the IOA method, on the other hand, AM was detected for 24 reports. With 32.2%, the proportion of AM detection was the highest when residents reported to hear noise that they perceived to be at least somewhat annoying, while the proportion was much lower when residents reported not to hear WT sounds. Yet, case numbers are too low to test for a significant correlation. With regard to maximum AM depth, differences are found for different levels of annoyance, although the overall effect is rather small ($\eta^2 = 0.09$). Specifically, maximum AM depth is, on average, larger for reports with at least medium annoyance ("somewhat annoyed") than for reports with lower levels of annoyance (Cohen's d between 0.27 and 0.61, i.e. small to medium effect sizes, see [21]). However, the AM depth can reach a similar order of magnitude for reports without heard WT sound compared to reports when residents were at least somewhat annoyed (see Tab. 6).

Figure 22 shows all AM data at the building against the wind direction, WT rotational speed and power output at hub height during the entire measurement campaign. The residents' complaints for the different annoyance levels are added as a function of AM depth and WT data. Note that the annoyance data is displayed so that the maximum values are in front. Data that have been removed (filter criteria in Sect. 3.1) only coincide with one report for which annoyance was not reported. Although the level of annoyance varies greatly when AM is present, most complaints tend to be around cross-se wind, rated rotational speed and are evenly distributed over power capacities between 40% and 100%. However, the same tendency is present when no AM is detected.

5 Discussion

It has been demonstrated that AM from WTs can be detected in both, acoustic and ground motion data. In this work, the established IOA method was applied to the acoustic data and, to the authors' knowledge, for the first time to ground motion data. Furthermore, a method developed to fit the AM in largely unprocessed data was applied to both data sets. Both methods gave similar results for the acoustic and ground motion data sets. However differences occurred between the applied methods. Compared to the SPP method, the IOA method detects AM 3–6 times more often in all data sets (Figs. 14 and 16). In the ground motion data, AM was mainly found at the wind farm site, whereas AM was also found in the acoustic data at the building site.

For the application of the SPP method, the amplitude modulated carrier tone must be known exactly. This prerequisite makes this method less flexible as it is designed specifically for one application, as WT type and the specific amplitude modulated tone must be known in a certain operating range. Since the IOA reference method considers a wider frequency range, it takes into account multiple tones that may be amplitude modulated. It is shown in Figure 6 that in the ground motion as well as in the acoustic data near the WT, the carrier tones 57.8 Hz (related to the generator) and 133 Hz are amplitude modulated during rated WT operation. Furthermore, the IOA method takes a wider operating range of the WT into account and thus AM during speed fluctuations, if the frequency range of the fundamental frequency is selected accordingly. However, the SPP method is simpler and requires fewer pre-processing and processing steps compared to the IOA reference method. The investigation finds, that ground motion data are in principle also suitable for the analysis of AM caused by WTs and that AM transmission may not just be an aeroacoustic phenomenon.

Using the IOA reference method, AM is detected less often at the building compared to the wind farm, but with similar AM depth. Larsson and Öhlund [23] showed that AM is influenced by the propagation path or interference of several WTs and thus the occurrence of AM at source and receiver may differ and have low correlation. Jennings and Kennedy [30] mention higher background noise or other noise sources hindering AM detection. However, an investigation of AM in relation to A-weighted sound pressure level $L_{A,\mathrm{eq,10min}}$ showed no clear indication that AM is only present at lower $L_{A,\mathrm{eq}}$, i.e. lower background noise. Since there were no wind speed measurements at the building location, masking due to wind cannot be clearly verified.

With regard to the wind speed at hub height, the methods differ for the considered two-week period. While the SPP method detects AM in a range of 7–11 m/s with a maximum SPP at 8 m/s, the IOA method detects AM for a wider wind speed range between 5 m/s and 13 m/s with highest AM depth above 10 m/s. As mainly southeasterly winds prevailed during the investigated two-week period for the IOA and SPP methods, no generally valid statement can be made about wind direction. However,

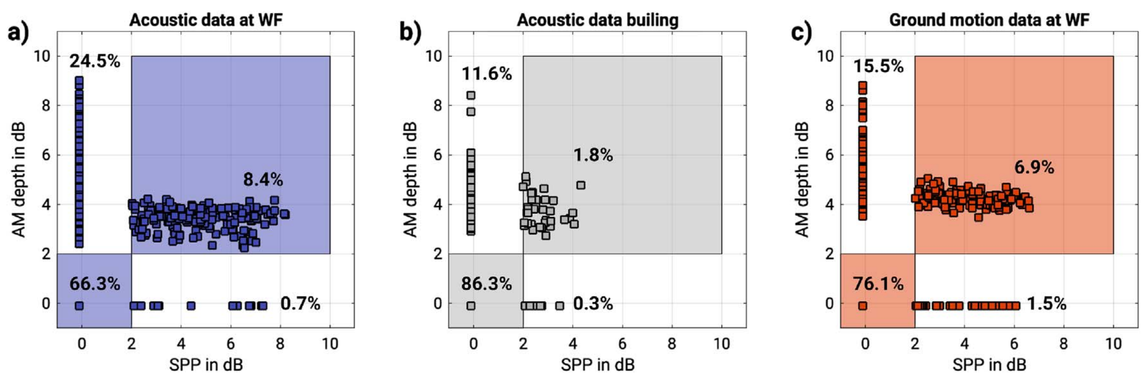

Figure 16. AM depth vs. SPP for all considered time windows from 2022/04/16 to 2022/04/29 for (a) acoustic data from the wind farm, (b) acoustic data from the building location, and (c) ground motion data from the wind farm. The displayed percentages add up to the numbers shown in Figure 15 and Table 5 and shaded areas highlight regions with detections or nondetections consistent between both methods.

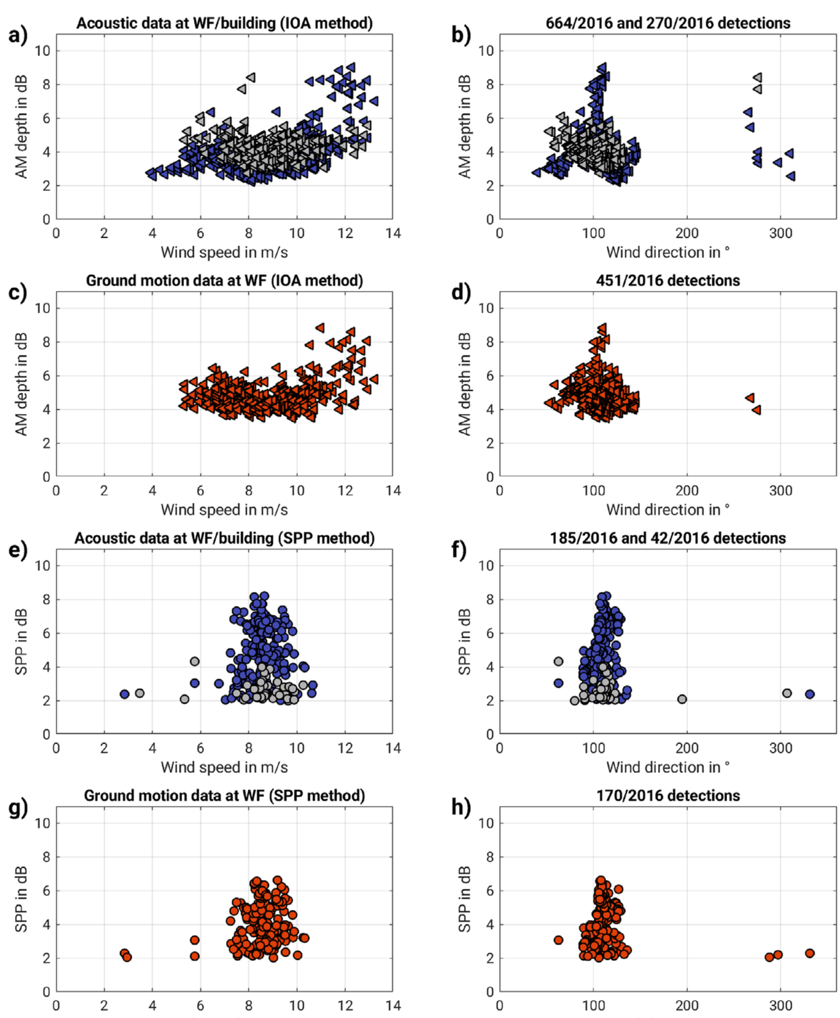

Figure 17. Results for AM detection in acoustic (blue and grey symbols) and ground motion (red symbols) data for 2022/04/16–2022/04/29 versus wind speed (left column) and direction (right column) using the (a)–(d) IOA and (e)–(h) SPP methods. Blue symbols show results for measurements at the WF and grey for those at the building location.

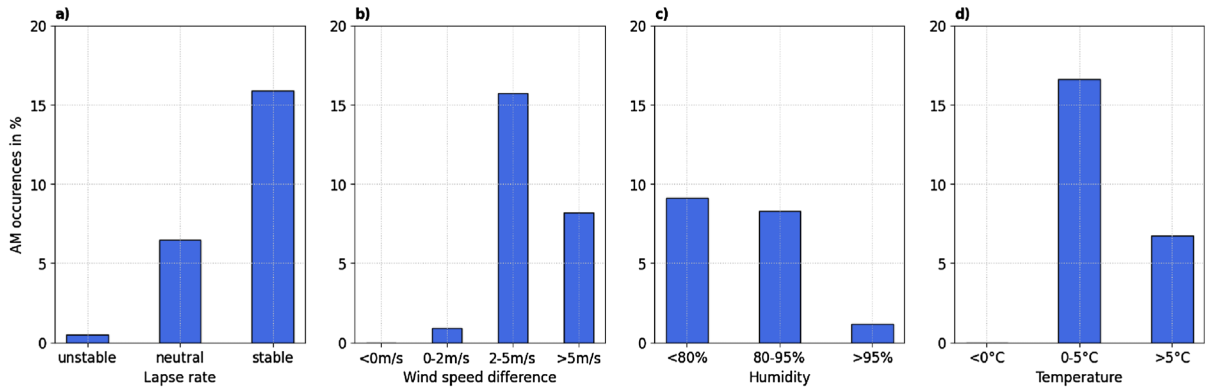

Figure 18. Normalized AM occurrence detected with the IOA method from 2022/03/24 to 2022/05/11 at the building location for different meteorological parameters from the WINSENT test site. (a) Lapse rate indicating unstable, neutral and stable atmospheric conditions, (b) wind speed difference for wind speeds at 11 m and 98 m, (c) humidity in 3 m height and (d) temperature in 3 m height.

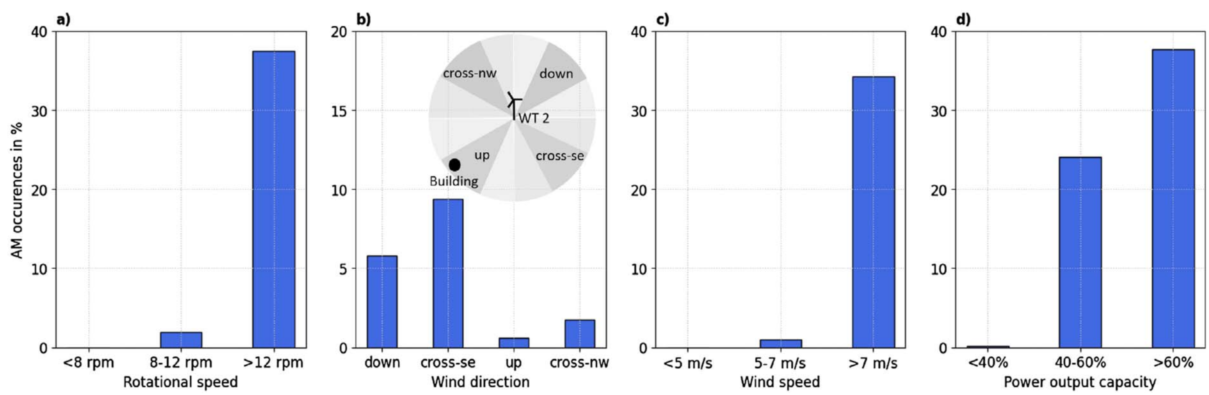

Figure 19. Normalized AM occurrence detected with IOA method from 2022/03/24 to 2022/05/11 at the building location for different WT operational parameters from WT 2 at hub height. (a) Rotational speed, (b) wind direction, (c) wind speed and (d) power output capacity.

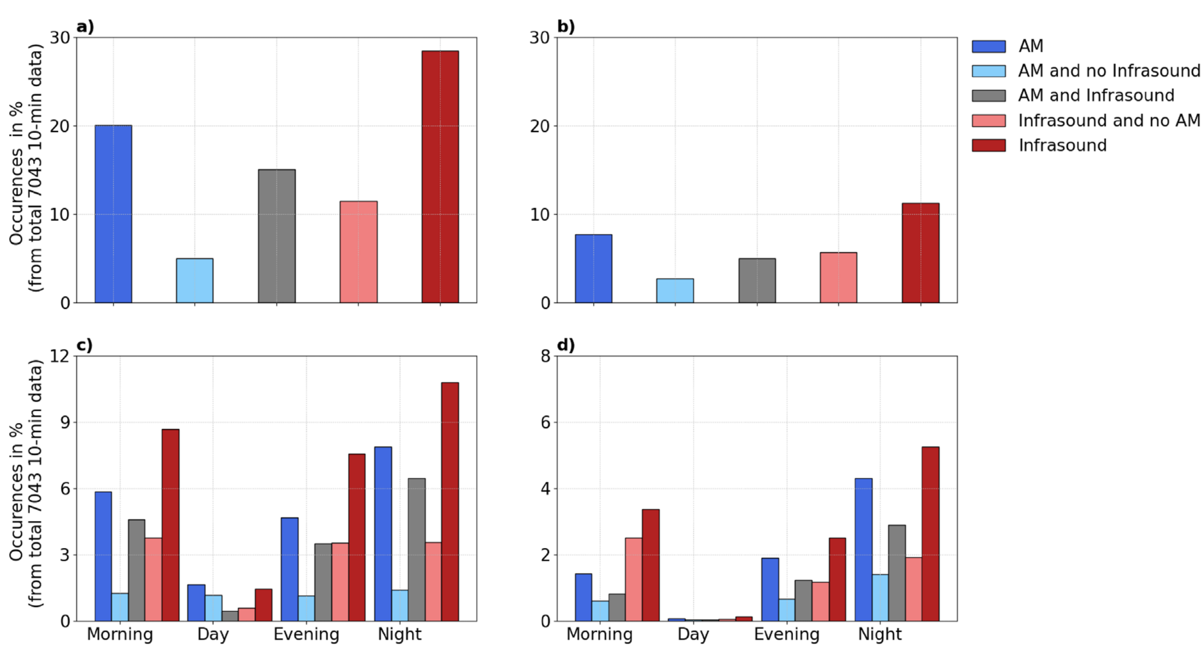

Figure 20. AM and infrasound occurrence from 2022/03/24 to 2022/05/11 for the (a) wind farm and (b) building location. Variation of AM and infrasound during day and night time for the (c) wind farm and (d) building location.

Table 6. Frequency of residents' noise reports with AM, and AM depth. Noise reports are grouped by self-stated audibility of WT sounds, and level of annoyance (LoA). LoA is measured on a scale of 0 (not at all annoyed) to 4 (very annoyed). M = mean, SEM = standard error of the mean. F, p, η^2: test statistics for analysis of variance.

AM (IOA)	Noise reports				Test statistic
50–200 Hz	No noise	LoA = 0	LoA = 1	LoA ≥ 2	
Not detected	115 92.7%	13 76.5%	16 94.1%	21 67.7%	
Detected	9 7.3%	4 23.5%	1 5.9%	10 32.3%	
Maximum AM depth (dB)	$M = 0.34$ SEM = 0.14	$M = 0.98$ SEM = 0.38	$M = 0.30$ SEM = 0.38	$M = 1.57$ SEM = 0.28	$F(3) = 5.72$ $p < 0.001$, $\eta^2 = 0.09$
Range (when detected)	3–6	3–5	5	3–7	
AM (SPP)					
Not detected	123 99.2%	16 94.1%	16 94.1%	31 100.0%	
Detected	1 0.8%	1 5.9%	1 5.9%	0 0.0%	
Maximum SPP (dB)	$M = 0.57$ SEM = 0.04	$M = 0.64$ SEM = 0.17	$M = 0.79$ SEM = 0.24	$M = 0.68$ SEM = 0.09	$F(3) = 1.13$ $p = 0.340$, $\eta^2 = 0.02$

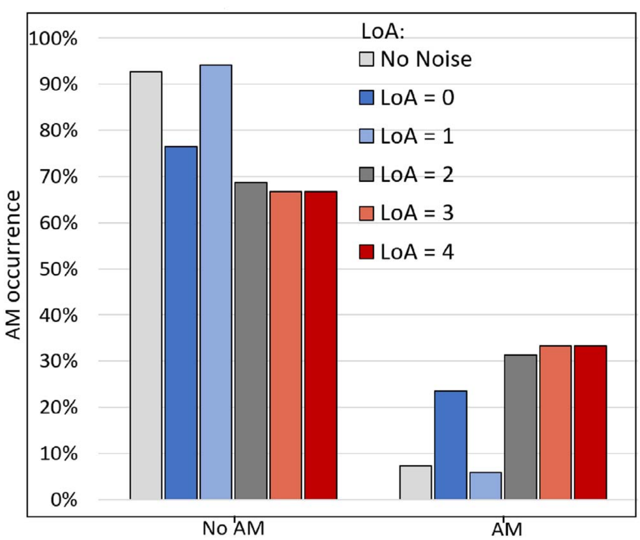

Figure 21. Occurrences of AM, and no AM during noise reports for different levels of annoyance (LoA, 0 "not at all annoyed", 4 "very annoyed") with the IOA method.

Figure 17 suggests that AM can be detected mainly in crosswind directions. Consideration of the longer measurement period (Fig. 19) supports this statement, since AM can also be detected mainly in crosswind and downwind direction at the place of immission. Similar results were obtained by Hansen et al. [15], Conrady et al. [21], Jennings and Kennedy [30].

It has been shown that acoustic AM at 1 km distance from the wind farm occurs particularly at night, as well as in the morning and evening hours. This can be attributed to the meteorological conditions such as a positive lapse rate. With a colder air layer near the ground, the sound waves are diffracted downwards towards the point of immission [23]. The occurrence of AM is mainly related to rated rotational speed but a power capacity between 40% and 100%, which is in agreement with Hansen et al. [15].

Since AM is a periodic fluctuation related to the BPF, occurrence of AM and infrasound was investigated and parallels were found in some time periods. The study showed, that AM is detected to a greater extent at the wind farm and at the building when infrasound is also present. While infrasound at a distance of 1 km tends to be below the human hearing threshold [5], the low-frequency tones at 57.8 Hz and 133 Hz are above it. If these are amplitude modulated by the passage of the blades and vary in loudness, this might be perceived as annoying by the residents.

With the lower detection rate of the SPP method, a correlation between AM and residents' annoyance could not be established, while the IOA reference method yields both a higher rate of AM detection and an associated AM depth of 3–7 dB, when residents reported higher levels of annoyance. This is in line with a study by Jennings and Kennedy [30], where 3 dB is defined as the threshold for annoyance. Yet, AM was present in about a third of the resident reports with higher levels of annoyance and a considerable amount of noise reports could not be attributed to AM. By evaluating the entire hour leading up to each noise report, a liberal method was used to connect AM to the reports, and still AM was absent for a lot of cases. However, this is plausible, as, apart from acoustic phenomena, research has shown that situational as well as subjective factors, such as attitudes, the perception of fairness (regarding the planning process as well as the distribution of costs and benefits) or noise sensitivity (e.g., [35–37]), have a strong influence on residents' noise annoyance. In a study by Janhunen et al. [22], no correlation between indoor AM and audibility of WT sound was found. However Hansen et al. [38] notes, that instead of indoor AM especially outdoor AM is related to annoyance, which may be due to the fact that the AM depth in the building is lower and thus less perceived, but also detected to a lesser extent due to a lower signal-to-noise

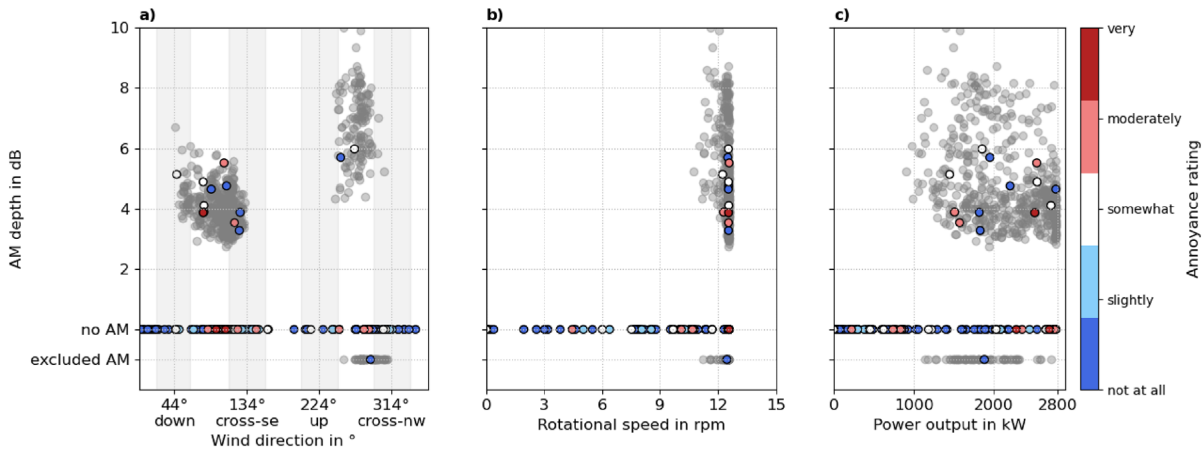

Figure 22. All AM depth data from the building location for (a) wind direction, (b) rotational speed and (c) power output of WT 2 in grey with color-coded annoyance levels from residential noise reports. Reports occurred during AM occurrence, no AM and AM excluded due to filtering.

ratio. This supports the procedure of primarily investigating outdoor AM in further studies. To derive valid relationships, the data set should cover several weeks to months with a sufficient number of reports. In addition, the quality of the AM data set could be improved by identifying AM occurrences by a human scorer [33]. However, this requires the input of an experienced acoustician familiar with AM characteristics in the time and frequency domain, which was not available within the scope of this project.

Some limitations of the study can be addressed in the future. Due to the required rated operation of the WT (for the SPP method), only a relatively short time period could be investigated for the comparison of the SPP and IOA reference methods. An extension of the study to include further measurement campaigns is planned. This would also benefit analysis of the relation of AM to annoyance. A lot of effort went into encouraging residents to continuously report audibility and annoyance over an extended time period, yet the density of subjective data is limited by the residents' willingness and ability to spend their time doing so, especially as they did not receive financial compensation for their effort. Further data on annoyance would help formulate more general statements. Moreover, WT 3, which is closest to the town of Kuchen, was out of operation during the period under consideration. Therefore, measurement data with operation of this WT should also be examined with regard to AM.

6 Conclusion and outlook

In this interdisciplinary study, an approach is proposed to investigate AM of WT emissions in acoustic and ground motion recordings. For this purpose, the IOA reference method and a newly developed SPP method, analysing the prominence of side peaks, are applied. For the comparison, rated WT operation is considered. Differences are mainly a consequence of the method used to detect AM (IOA or SPP), and not so much affected by the choice of data (acoustic or ground motion). With the IOA method, the AM detection rate is 3–6 times higher than with the SPP method. The results indicate that ground motion data are in principle also suitable for the investigation of WT-related AM. This is beneficial as ground motion recordings are less affected by environmental conditions than acoustic recordings, but the prominence of signals affected by AM decreases more rapidly with distance from the WTs. In the measurement campaign ground motions have been recorded at several additional locations complementing the acoustic measurements. This enables the investigation whether WT emissions are more likely to propagate through the air or the ground.

For the acoustic data, it was found that at 1 km distance AM occurs during stable atmospheric conditions (in the night, morning and evening hours). Dependencies on wind direction have not been found, because mostly crosswind conditions occurred during the measurement campaign and no strong tendencies were found in the evaluation. The SPP method detected fewer instances of AM at higher wind speeds compared to the IOA method. Furthermore, AM depth evaluated with the IOA method increases with increasing wind speed.

When residents report at least a medium level of annoyance, results show, that AM is most likely detected with the IOA reference method. However, the evaluation shows that the SPP method cannot explain the annoyance of residents, since there were too few AM detections available. With the SPP method, AM is hardly detected in the acoustic data at the building location. Furthermore, for the comparison of annoyance and AM detections with the IOA method, more noise report data (regardless of whether noise was perceived or not) from further measurement campaigns are required. This is necessary to provide a statistically meaningful result for the correlation of annoyance with AM. However, both methods can be used simultaneously and provide a useful tool for AM detections, since AM might be more likely present when both methods detect AM. In the future the methods will be applied to data sets from further measurement campaigns in order to validate the described results.

Conflict of interest

The authors declare no conflict of interest.

Data availability statement

Data are available on request from the authors.

Acknowledgments

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