The wind effect on sound propagation over urban areas

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The wind effect on sound propagation over urban areas: Experimental approach with an uncontrolled sound source

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ABSTRACT

Urban sound propagation is influenced by meteorological conditions, causing refraction and scattering of sound waves. An experimental study on the effect of meteorology on urban sound propagation has not been addressed yet on long-term and long-range scales. For the first time, this paper presents an approach to measure the wind effect on urban sound propagation from an uncontrolled sound source. The approach is applied to a location in Eindhoven (the Netherlands), with church bells as the source of sound. Sound is continuously measured, downwind from the sound source according to the prevailing wind direction up to 527 m from the source, and during a period of 5 months. Results of this measurement campaign show an increase of the sound pressure level of 0.4 dB, 0.8 dB, and 1.9 dB across three measurement positions per 1 m/s increase of the wind velocity over 1/3rd octave bands. Effects are stronger for lower frequencies and increases for further microphone positions. Possible future improvements of the experimental approach are discussed.

1. Introduction

Addressing environmental noise problems has been a major focus area among policy makers in Europe [1]. Traffic noise, the second most common source of pollution, causes a range of health problems like annoyance, sleep disturbance, tinnitus and cardiovascular diseases. To combat these harmful effects of noise, environmental studies have been undertaken to monitor the propagation of sound in outdoor environments. Major factors influencing outdoor sound propagation are meteorological effects due to wind, temperature, turbulence and humidity, causing refraction, scattering and air absorption of sound waves. The second set of factors influencing urban sound propagation is the urban topology, causing reflection, absorption, and diffraction of sound waves upon interaction with the ground, vegetation, buildings, and other objects. In urban areas, many noise sources are typically shielded by buildings, potentially leading to favourable quiet areas [2]. However, due to meteorological effects, shielded (distant) noise source may propagate over the urban topology and increase noise levels [3,4]. Engineering methods like ISO 9613-2, NMPB-Routes-2008, Harmonoise and CNOSSOS-EU were developed to produce noise maps based on (inter)national and European standards. Though these methods do consider meteorological parameters like wind, temperature and air absorption, they lack an appropriate quantification of meteorological effects on distant propagation in urban areas [5,6] as they are based on the principles of geometrical acoustics or ray-based methods. More advanced wave-based methods have been developed too [7,8].

Experimental studies on meteorological effects on sound propagation have been carried out from long back, as in 1975 [9], when a range of measurements to observe atmospheric effects on aircraft flyover noise was done by NASA scientists Hosier and Hilton. In the 1980s and 90s, the refractive effects of wind and temperature along with ground effects were studied, and a strong meteorological impact on sound propagation was found [10,11]. These studies had been done in controlled environments where the terrains were mostly flat with very few or no obstructions. Later on, experiments were carried out including more terrain effects. In 2006, outdoor measurements were carried out to validate a numerical method, Green’s function parabolic equation (GFPE) [12]. The study involved sound propagation from road traffic into a valley of mountains, away from urban residential areas. In 2013, Evans and Cooper presented a monitoring study done on the effect of winds on propagation of wind turbine noise [13]. The sites used for measurement in this study are a wind farm and a mountain ridge with microphones placed on flat terrain and ridgelines respectively. In the same year, another study on long-term spatial and temporal variability of meteorological and acoustic parameters at an experimental site was published [14]. This experimental site is relatively complex compared to the previous open ground studies as it monitored meteorological effects through a viaduct along with propagation over a valley. One
study was published on meteorological effects on sound propagation in an urban area [15], with propagation from a courtyard into adjacent courtyard. An increase in the noise levels with increase in wind speed for the frequency bands of 630 Hz and 800 Hz is observed. A controlled loudspeaker source was used in this experiment and the distance to the farthest microphone was not more than 15 m, even if the microphone’s line of sight from the source was blocked. A recent study was conducted on the atmospheric variability of impulse sounds (gun shots, explosions) over a flat terrain under different wind directions [16]. The study shows how the propagation of transient signals is impacted by a combination of absorption, turbulence, mean refraction, diffraction, and ground reflection, even at a short distance of 100 m. The pulse shape undergoes major changes under the influence of range, wind direction and atmospheric turbulence.

As regards studies with an uncontrolled sound source, measurements of sound propagation due to road traffic noise into an open field was carried out by Oshima and li [17]. Meteorological data was collected through weather stations placed at acoustic measurement points. This study was done over 3 months of data and showed a clear decrease in excess attenuation with increase in wind speeds at distances of 40 and 140 m from the source. However, the propagation path did not have any buildings or barriers, except the sound barrier next to highway. In other words, though the experimental setup was uncontrolled, the propagation path did not include an urban area.

Thus far, a long term experimental campaign that studied the effect of wind on sound propagation into an urban area over a longer distance has not been conducted. Therefore, the aim of this paper is to present a methodology to quantify the effect of wind on distant urban sound using existing noise sources. In this work, only the effect of the mean wind is assessed for one urban scenario. One of the methodology given in Ref. [18] has been used to transform the statistical meteorological data to the sound measurement area. In future work, the methodology should be applied to more urban sites, such that simplified relations for the wind effect can be obtained that can be used for better predictions of meteorological effects by engineering methods.

In this paper, section 2 describes the rationale of obtaining the wind effect on urban sound propagation from the experimental data, as well as the measurement setup. In order to quantify the wind effect on noise levels, Section 3 presents the procedure used to analyze the obtained acoustic and meteorological data. In Section 4, the results of the measurement campaign are shown, followed by a discussion on the results. Section 5 gives the conclusions of this work and provides a path for future research.

2. Rationale of experiments and setup

We propose an experimental setup that allows to determine the influence of the mean wind effect on sound propagation between two positions in an urban area using an existing sound source, such that the frequency dependent effect of an increase (or decrease) of the vectorised mean wind velocity on the sound pressure level difference between the two positions can be quantified. It needs to be emphasized that the presented approach would also allow to study other meteorological effects on urban sound propagation as atmospheric turbulence and temperature profiles, but this is out of the scope of current work.

For the setup, the following conditions are defined for determining the mean wind effect:

- An existing sound source has to be present, whose sound pressure level (SPL) exceeds the background noise at the receiver locations to be able to quantify the mean wind effect. The power of the sound source, the local environment and other sources of sound determine the distance up to which the meteorological effect can be quantified. The sound source can be any source with sufficient sound power, for example be road or railway traffic;
- It should be possible to monitor the sound pressure level close to the sound source, such that meteorological effects between sound source and this measurement position are negligible. This measurement position will then scale with actual sound power;
- An urban area has to be situated in the opposite direction of the sound source with respect to the predominant local wind direction, in which microphones can be positioned to measure sound levels over a long time. As such, the mean wind effect for downward refracting direction will be captured.

In this paper, results from a first measurement campaign following the conditions above is presented. The measurements were carried out inside the city of Eindhoven. The sound source is a church bell, making periodic sound during the whole day and night. It is possible to measure the sound pressure level in the bell tower and a residential area is located in the east-northeast direction from the tower. The background noise in this area is mostly due to local road traffic noise, which is in particular low during nighttime.

2.1. Sound source

The source at this location is a church bell, located in the tower of the St. Trudo church in the Strijp area of Eindhoven. The church bell is not a representative of surface transport noise. It is used here exclusively for determining the wind effect, as church bells constitute one of the urban sound sources. The bell tower is about 40 m high and bell is positioned at a height of 38 m from the ground. This church is selected among other churches in Eindhoven, since the bell sound of this church is the most powerful. The tower has 3 bells that strike for different occasions. The biggest one strikes once every 15 min, and also every hour. During each hourly strike, the biggest bell strikes n number of times for every nth hour, which means the bell would strike once at 1 o’clock and 12 times at 12 o’clock, repeating this cycle every 12 h. The two other bells strike for special occasions like weddings and masses for the deceased. The bell is enclosed in a tower which has 4 open window-like outlets that allows the sound to propagate into the urban environment. Studies have been done to the power spectrum of bells and their harmonics [19]. In this work, only the propagation aspect of the bell sound is studied.

2.2. Receiver positions

Sound from the church bells propagates into the neighbouring residential areas, consisting of buildings with a 5 m–20 m height, urban terrain that includes streets, courtyards, backyards, gardens and parks, all of which have different material composition and as a result, different sound absorbing properties. As mentioned before, the measurement locations are selected in the east-northeastern side of the sound source in order to study the propagation effects in the downward refracting direction. The reference microphone, labelled RF, is placed at a distance of 1 m from the bells inside the bell tower and the measured sound pressure level scales with the sound power of the bells. Three microphone positions are selected along the downwind propagation path, in three residential locations at increasing distances from the source, as seen in Fig. 1. The local positioning of all four microphones is shown in Fig. 1.

The section layout of the measurement area is shown in Fig. 2. It shows the topology and surfaces around the source and the microphones RF, R1, R2 and R3. The horizontal distances and the vertical distances are approximate within a distance of 1 m and 0.3 m respectively. The horizontal distances shown in Fig. 1 are the shortest distances between the source and receiver on a horizontal plane. The shortest microphone R1 is located at 178 m from the source, and at a height of 4 m from the ground. As can be seen from Fig. 2, the location of this microphone is positioned on the first floor of a four-storied building. R1 is positioned on a balcony which overlooks a courtyard that is semi-circular in shape. The microphone is completely obstructed...
Fig. 1. The locations of the four receiver positions. The positions are RF (top left), R1 (top right), R2 (bottom left), and R3 (bottom right). \( h \) denotes height of the microphone from ground level.

Fig. 2. Cross-section layout of the source and receiver positions. The top figure shows the positions of the source and all receivers in the location. The next 3 figures below show the 2-D cross-sections of the Source S and receiver positions RF & R1, RF & R2, RF & R3, respectively. The horizontal distances are not proportional to the heights. All the distances in the figures are in meters.
from the view of the church tower due to its building orientation. The second measuring position R2 is placed behind a house on its back-façade. The distance between the microphone and the shed is 6.5 m. The distance of R2 from the source is 442 m and at a height of 3 m from the ground, geometrically shielded from the source’s line-of-sight by the opposite house. The last position, R3, is located on the roof of a house, in its backyard. The distance of R3 from the source is 527 m and the height is 4 m from the ground. Though R3 is shielded from the line of sight of the source, there is a quite large open space at the west (source-facing side) of the microphone while the east is flanked by the wall of the house. This location has relatively less shielding than R2 in terms of the structures surrounding the microphone, which could influence the wind effect.

2.3. Acoustic equipment

Class II outdoor microphones from ASAsense have been used for the measurements. The circuitry of the microphone is enclosed in a waterproof thermoplastic box, and powered via a 220V AC to 18V DC power adapter, which makes up the monitoring station. For R1, R2 and R3, this station is connected to the internet through two power-over-internet adapters, one of which is connected to the microphone and the other is connected to the central internet supply or WiFi router of the local house. These two adapters communicate to each other through wireless transmission. In the case of the reference position RF, since the bell tower does not have internet supply, a 4G/LTE internet dongle is used with a data subscription to provide a non-stop supply of internet. Sound pressure levels (SPL) in third octave bands at each position are recorded by the microphones every 0.125 s and sent to a server, which can be accessed remotely. The time stamp of each microphone is synchronized to a clock at the server.

2.4. Meteorological data

The wind data is obtained from the open access database of Royal Meteorological Institute of Netherlands (KNMI). The weather station of the KNMI in Eindhoven is located in only one location, at Eindhoven airport, which is located at a distance of 4.8 km from the bell tower. The location of the meteorological station along with its distance from the sound measurement area is indicated in Fig. 3a).

The obtained data consists of the averaged wind speed at 10 m above the ground and wind direction $\theta$, recorded in hourly samples. The data obtained from the meteorological station at the airport cannot be directly used for studying the wind effect at the urban area of the measurement, as they are located at a distance of 4.8 km apart.

As regards the wind field in urban areas, wind tunnel measurements and CFD calculations have been carried out to study the propagation of wind into urban areas [20–22]. These studies show that the propagation of wind into the urban area is majorly impacted by the surface roughness. An urban comfort study in 2009 [18] takes the effects of surface roughness on wind flow into urban areas into consideration and presents a methodology to transform the statistical meteorological data from weather stations to the urban location of interest. This methodology is also used in another study in 2012 [23] to predict wind comfort through CFD simulations for Eindhoven University of Technology campus.

Here, the local surface roughness at the measurement area differs from roughness at the meteorological station [18]. Therefore, the transformation method given by Ref. [18] is used based on aerodynamic information between the two sites. The aerodynamic information consists of terrain related contribution (change in wind statistics from the meteorological site to a reference location near the measurement area) and design related contribution (change in wind statistics due to the local urban design, i.e. the building configurations) [18]. The terrain related contribution in this work is represented through a gain factor $\gamma$ which is calculated through formulas (1) and (2).

$$\begin{align*}
\gamma &= \frac{U}{U_{\text{met}}} = \frac{u^*\ln\left(\frac{h}{y_0}\right) + 1}{u^*_{\text{met}}\ln\left(\frac{h_{\text{met}}}{y_0}\right) + 1}
\end{align*}$$

(1)

Fig. 3. a) A layout of the measurement area and Eindhoven airport, where the meteorological data is obtained from. b) Wind rose depicting wind speed and direction during the period of November 2017 to May 2018. The length of each colorbar represents the share of that specific wind speed class. The direction that the wind is blowing from is shown by the location of the wind speed classes in the wind rose. The frequency of wind speeds is shown in the ascending order of concentric circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
\[
\frac{u^*}{u_{net}} = \left( \frac{y_0}{y_{0,net}} \right)^{0.0706}
\]  

(2)

In the above formulas, \( U^* \), \( u^* \), \( y_0 \), and \( u_{net}, y_{0,net} \) are the wind velocities, friction velocities and roughness lengths at the measurement site (at 50 m) and the meteorological site (at 10 m), respectively. The roughness lengths \( y_{0,net} = 0.03 \text{ m} \) for the meteorological site and \( y_0 = 1 \text{ m} \) for the measurement area are obtained from Davenport roughness classification standards for cities and sheltered country [24]. The calculated gain factor \( y \) is multiplied with the wind velocity at the meteorological station to obtain the wind velocity at the measurement site at a height of 50 m. The direction of wind between both the sites is not expected to be different since the terrain between both the sites comprises of urban farms and smooth urban obstacles with modest heights measuring not more than 25 m. The design related contribution at the measurement site, which transforms the wind statistics at 50 m to the microphone height level, requires wind measurements and CFD simulations which is not within the scope of this work. Even if the wind statistics at microphone height would have been available, this data at the low heights between urban obstacles will likely not correlate with changes in sound pressure levels. Therefore, the height of interest for this study is kept at 50 m with respect to wind statistics and the design related contribution is not included.

The wind velocities and direction during the measurement period of 7 months is depicted through a wind rose in Fig. 3b. It could be observed that dominant direction of wind during this period is from southwest, which is also the direction in which the highest values for wind speeds are observed. The direction of wind approximately aligns with the downwind direction of sound propagation from source to receiver as could be seen from Fig. 1.

3. Data analysis

3.1. Acoustic analysis

In order to analyze the effect of wind on sound propagation, the sound from the source, which in this case are church bells, has to be separated from the other sounds recorded at the receiver position. The recorded data has to be processed with conditions to exclude data polluted with background noise. A procedure to analyze the data is here described, tailored to the current situation. In a modified version, it can be applied to other situations with other noise sources as well.

The data collected remotely from the server consists of sound pressure levels at a resolution of 8 samples per second, for every 1/3rd octave bands from 20 Hz to 20000 Hz. The data is collected over a period of 7 months, from November 2017 to May 2018. Though the bell strikes every 15 min every day, the hourly strike is selected as the source as it increases in the number of gong-hits each hour. The data for the first minute of every hour is separated from the remaining minutes. \( L_{50} \) and \( L_5 \), which are percentile values of the sound pressure levels over the selected time period, are calculated over this minute. \( L_{50} \) is used as an indicator for background noise and \( L_5 \) is used to represent the sound level from the church bells, at least in the first minute of every hour. Before analyzing the results at R1-R3, the frequency range for which the church bells have sufficient acoustic energy has to be determined. The spectral \( L_5 \) values at the reference position RF are therefore analysed for the first minute for 8 h between 23:00 and 7:00 every night, as shown for a sample night in Fig. 4. The spectrum shows the averaged tonal behavior of the church bell, with a fundamental frequency in the 160 Hz 1/3 octave band and a series of overtones. From Fig. 4, only bands that exceed 80 dB at RF are selected, for that specific night.

Fig. 5 shows the flowchart of the process to extract the data-hours that represent sound pressure levels that are measured as representing sound from the church bell at the receiver positions R1, R2 and R3. The analysis is performed hourly, but during night-time hours only as the background noise levels are lowest during this period. The diamond box represents a condition set at R1, R2 and R3 to check if the sound pressure levels capture the sound from the bell. The criterion states that an hour is picked only if the \( L_{50}-L_{5} \) value of the 1st minute is at least 3 dB larger than from the previous minute (60th minute of the previous hour) and from the next minute (2nd minute of the current hour). The selection of 3 dB is a trade-off: using a larger difference is preferable for reducing the effect of background noise on the results but also implies that sound pressure levels from the church bells closer to \( L_{50} \) will be filtered out, meaning that for low (or negative) wind velocities, no data would have passed the filtering condition. Each frequency band is analysed independently of each other and the condition is looped over the selected hours. Only those hours that satisfy the criterion are selected. An analysis is done for the selected hours of data as a function of the wind velocity. The transformed wind velocities are vectorised with respect to the source-receiver direction, according the following equation

\[
U_{5,Rx} = U \cos(\delta_{5,Rx} - \theta_u)
\]

(3)

where \( \delta_{5,Rx} \) is the angle of the source-receiver vector with respect to the north direction vector, \( \theta_u \) is angle between the wind direction vector with respect to the north direction vector, \( U \) is the mean wind speed and \( U_{5,Rx} \) is the vectorised mean wind velocity. The above expression multiplies \( U \) with a maximum positive weighting of 1 when the wind direction is the same as source-receiver direction and a minimum negative weighting of −1 when the wind is blowing from the opposite direction.

3.2. Statistical analysis

The trends in wind effects on noise over the measurement period is presented through statistical analysis. A regression line is fitted through the level differences \( \Delta L_{5,Rx} = L_{5,Rx} - L_{5,RF} \) over the vectorised wind velocity \( U_{5,Rx} \), where \( Rx \) could denote position 1, 2 and 3. The line is obtained by finding the coefficients of the polynomial given in equation (4) through a least squares method.

\[
\Delta L_{5,Rx,p} = C_{Rx} + P_{Rx} U_{5,Rx}
\]

(4)

The quantity \( \Delta L_{5,Rx,p} \) is the predicted level difference from the linear model. The coefficients \( C \) and \( P \) are determined with a confidence estimate of 95%. The intercept \( C \) is the level difference at zero wind velocity while the slope \( P \) is the level difference at unit vectorised wind velocity. The standard deviation of the predicted \( \Delta L_{5,Rx,p} \) from the measured \( \Delta L_{5,Rx} \) is calculated through a root mean square algorithm as given in equation (5), where \( N \) is the total number of data points.

\[
\sigma_{Rx} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\Delta L_{5,Rx,i} - \Delta L_{5,Rx,p})^2}
\]

(5)

The \( \Delta L_{5,Rx,p} \) is plotted against \( U_{5,Rx} \) as a linear function in this model. Oshima and Li also used a linear regression model in their analysis of
wind effect on traffic noise propagation over a flat ground [17], and this work tries to compare the findings with their work. More importantly, the data available from the meteorological station is in hourly samples, which makes the data in Figs. 6–8 too scattered for using a higher order regression function. To monitor the reliability of the regression, the following four conditions are set [25].

a) The dataset of the variable used to evaluate the model should be within the range of the sample data used to build the model. In this work, this is ensured by using the same variable $U_{5, R1}$ for fitting the polynomial to a linear function as well as for evaluating the polynomial, for all the three measurement positions.

b) The slopes of the regression lines should be non-zero.

c) The residuals of the model should be normally distributed.

d) The $R^2$ value, called the Coefficient of Determination, accounts for the variance of the regression model. The value is defined through the following equation

$$R^2 = \frac{\sum_{i=1}^{N} (\Delta L_{5, R1}(i) - \bar{L}_{5, R1})^2}{\sum_{i=1}^{N} (\Delta L_{5, R1}(i) - \bar{L}_{5, R1})^2}$$

where $\bar{L}_{5, R1}$ is the mean of sample data used to build the model. Though there are no universally accepted $R^2$ values for determining the reliability of a model, generally the higher the value, the better is the model to fit the data. All $R^2$ values fall between 0 and 1.

### 4. Results

#### 4.1. Wind effect at the three receiver locations

Fig. 6 shows the scatter plots of the level differences $\Delta L_{5, R1}$ plotted as function of $U_{5, R1}$. The regression is denoted by a yellow line and the standard deviation from the regression is denoted by the two dotted black lines. The data points whose residuals aren’t normally distributed and are outliers, are colored in red.

The data shown here is the set of hours that satisfy the criteria explained in Fig. 5. Since the algorithm is looped over all 1/3 octave bands separately, a different density of data points can be seen for different frequency bands in Fig. 6. The frequency bands shown, have enough data points to show a trend and obtain regression lines. These bands satisfy the condition that they should contain at least 10% of the total data samples collected from the measurement period. In this study the number of samples is 1560 data points or hours, which means the frequency band should contain at least 156 h. The trends with respect to position R1 in Fig. 6 show a clear increase in level difference $\Delta L_{5, R1}$ with the increase of the vectorised wind speed. A positive slope satisfies condition b) of the regression validity check. The outliers whose residuals don’t satisfy condition c) are denoted in red. This model has a mean $R^2$ value of 0.0897, which is considered low. However, a low $R^2$ value does not mean an inherently bad prediction since the most significant quantity is the mean level difference per unit vectorised wind velocity, or the slope $R_{5, R1}$, which is positive for all the frequency bands.

The scatter plots and regression lines for position R2 are shown in Fig. 7.

These plots show again that there is an increase in the $\Delta L_5$ value with increase in the downwind component of the wind speed. However, the number of data points in these plots is lower than that of the position R1, because the conditions of Fig. 5 considerably filter out more hours that do not meet the criteria due to the lower sound levels of the church bells at the farther distance. Some bands did not have enough data points to cross the 10% of the total number of points available. Only 8 bands are selected for the analysis. All these bands show that
wind has a considerable impact on the noise levels at position R2 as well.

The regression reliability checks for position R2 indicate satisfaction of conditions a), b) and c) whereas the mean $R^2$ value over the spectrum is 0.1037.

Fig. 6. Scatter plots showing $\Delta L_{R1}$ levels over vectorised wind speeds $U_{S,R1}$. The plots include regression lines fitted with least squares method to the data, with the red line showing the mean line and the dotted black lines showing lines with a standard deviation from the average. The bands shown here are selected based on the number of data points. Red colored data shows the outliers in terms of their residuals not having normal distribution. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 8 shows the scatter plots and regression lines for position R3. The number of data points that satisfy the filtering criterion is even lower than at position R2. There are only 2 bands that contain sufficient number of data points to cross the 10% minimum limit. Both these bands show a clear increase in noise level differences with increase in
wind speed of the western component. The regression for these two bands satisfy checks a), b) and c), with the outliers for c) represented in red in Fig. 8. The mean \( R^2 \) value over the spectrum 0.22 is higher than positions R1 and R2.

Fig. 9 presents the slopes of the regression lines \( PR_x \) as a function of the 1/3 octave band and for the three locations. In Fig. 9a, the slopes for position R1 ranges from 0.18 dBsm\(^{-1}\) being the lowest at 2500 Hz to 0.61 at 400 Hz being the highest. At the position R2, 0.33 dBsm\(^{-1}\) is the lowest slope at 2500 Hz, and 1.65 dBsm\(^{-1}\) is the highest 315 Hz. At position R3, the highest slope is 1.94 dBsm\(^{-1}\) at 315 Hz and the lowest slope is 1.80 dBsm\(^{-1}\) at 630 Hz.

The mean of standard deviation per frequency band is shown in Fig. 9b. It shows that as the distance from the source gets larger, the standard deviation of the regression line on the results is higher, as shown by the standard deviations from R1, R2 and R3. The standard deviation has an averaged value of 3.2 dB for the selected bands at position R1, followed by an average value of 4.7 dB for R2 and of 7.1 dB for R3.

Fig. 7. Scatter plots showing \( \Delta L_{S,RZ} \) levels over vectorised wind speeds \( U_{S,RZ} \).
4.2. Discussion

The averaged level differences per unit vectorised wind velocities $P_{Rx}$ over 1/3rd octave bands increases with increase in distance from the source, with values of 0.42 dB sm$^{-1}$, 0.82 dB sm$^{-1}$ and 1.87 dB sm$^{-1}$ for R1, R2 and R3 respectively. This is expected since the refractive effects of the wind velocity gradient increases with increase in distance. The averaged excess attenuation over frequency in Oshima and Li’s work [17] falls between the range of R1 and R3, with a value of 0.7 dB sm$^{-1}$. The excess attenuation in Ref. [17] was measured at a distance of 140 m, which is even less than the distance of the first position R1 in this study. However, the topology in Ref. [17] is a flat field without any shielding between the source the measuring position, whereas the topology between the source and positions R1, R2 and R3 consist of buildings that shield these positions from the source. Moreover, the building structures and their materials around the three positions are different which could have an impact on the wind effect. The parameters involving the effects of local environment are complex, which could be the topic of future studies and computations.

The overall wind effect on sound propagation in R2 is also frequency dependent as it can be seen from Fig. 9. A relatively larger wind effect is observed in lower frequencies of 350, 400 and 630 Hz. Usually, for a single receiver position, the effect of wind increases with frequency, as higher frequencies correspond to a large number of travelled wavelengths, as shown by Ref. [4] even for an urban location. However, R1 does not show any perceivable trend with frequency and higher frequencies at R3 does not have higher frequencies that satisfy the filtering criterion, so the consistency of the frequency dependent observation cannot be confirmed. The decrease in number of data points that satisfy the filtering criterion at positions R2 and R3 could be explained by the decrease of the sound energy of the church bells at these locations. Since the criterion essentially ensures that the sound recorded by the microphones at these locations is primarily from the church bells, the contribution from church bell at these locations is not high enough for most 1/3 octave bands. A computational study of the wind effect on sound propagation [4] predicted the higher frequencies to have more impact from the wind. However, in Ref. [4] the source was positioned at 0 m on a road in a street canyon, whereas the source in this study is positioned at a height of 38 m.

Similar to the current urban scenario, Oshima and Ii [17] performed an experimental campaign to quantify wind effect over flat ground, with distances of 40 and 140 m. A standard deviation of 2 dB was observed for their data at their measurement points. The reason for higher standard deviations for the current work in comparison to [17] is because of the difference in the measurement scenarios and the sampling of meteorological data in both studies. The study in Ref. [17] was done on a flat field including direct sound propagation to the receiver. Only the ground effects was involved and no barrier or obstruction was in

![Fig. 8. Scatter plots showing $\Delta L_{R1,R3}$ levels over vectorised wind speeds $U_{S,R3}$.](image)

**Fig. 8.** Scatter plots showing $\Delta L_{R1,R3}$ levels over vectorised wind speeds $U_{S,R3}$.

![Fig. 9. a) Slopes of the regression lines from Figs. 5–7, b) Standard deviation $\sigma$ from regression lines in Figs. 5–7.](image)

**Fig. 9.** a) Slopes of the regression lines from Figs. 5–7, b) Standard deviation $\sigma$ from regression lines in Figs. 5–7.
place. This means that the sound pressure level due to the investigated noise source over the background noise level was likely much higher in Ref. [17]. Moreover, the sampling of meteorological data was done on 30 s samples collected from an in-situ meteorological sensor, whereas the meteorological data in this work is obtained from a weather station at the airport of Eindhoven, which is located at a 4.8 km distance from the measurement area. Further, the hourly sampling of meteorological data could be too coarse for the analysis, while the noise data are analysed for 1 min periods only. Therefore, local wind fluctuations both in space and time scales could have led to the increase in standard deviation in this study. The increase in average standard deviations in this study with distance indicates a lower correlation of the predicted level differences $\Delta L_{i,j}, P$ from the observed level differences $\Delta L_{i,j}, R$ with increase in distance. This is a result of a wider scatter of data points which arise due to the reasons mentioned above.

5. Conclusions

For the first time, this study attempts to observe the effects of wind on sound propagation from an uncontrolled source into an urban residential area over a longer distance. For the installation of the measurements equipment, conditions were set for the chosen sound source, a location for a microphone measuring its relative sound power, and locations to be used for the receiver positions with respect to the dominant wind direction. A data analysis procedure is proposed such that sound pressure level data measured at receiver locations can be attributed to the sound from the chosen sound source.

As a first study, a location in the city of Eindhoven is chosen with church bells as the source of sound and microphones located at the east-northeast direction from it. Results have been analysed between 315 Hz and 2500 Hz as the church bells have sufficient power in most of 1/3 octave bands inside this range.

The main conclusions are as follows:

- Sound levels in the urban residential area increase with the increase in mean wind speeds, and a linear regression analysis has been done to obtain the wind effect in $\text{dB} \cdot \text{m}^{-1}$. An average slope of 0.4 $\text{dB} \cdot \text{m}^{-1}$, 0.8 $\text{dB} \cdot \text{m}^{-1}$, and 1.9 $\text{dB} \cdot \text{m}^{-1}$ across the three measurement positions over the 1/3rd octave bands was found;
- The impact of wind on sound propagation varies with frequency. At one of the three positions, larger wind effects are found in lower frequencies. However at the other two positions, this trend cannot be confirmed;
- The average standard deviation of the $L_{i}$ values against vectorised wind speed increases with the receiver position: 3.2 dB for the position at 178 m, 4.7 dB at 442 m and 7.1 dB at 527 m. The coarse sample rate of the meteorological data and the distance of the weather station from the measuring locations has influenced these large standard deviation, especially at the farthest position.
- Distance from the source impacts the meteorological effects on sound levels: the wind effect is larger for larger distances.

Though the analysis of wind effect on sound propagation has shown clear trends for certain frequencies, these trends could also have been influenced by other meteorological factors like temperature, atmospheric turbulence, humidity and cloud cover. The uncertainties arising from these factors should be taken into account in further studies. Also, a local meteorological sensor will decrease the uncertainty of the results. This study is the first of its kind with respect to monitoring wind effects from an uncontrolled source into a real urban environment. The point-like church has a high elevation, and the found wind effects are not directly representative for sound sources on the ground surface. Future work will include a similar analysis for other source types, as road and rail traffic, in different urban configurations.

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