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Structure-borne sound and vibration from building-mounted wind turbines

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Abstract
Noise continues to be a significant factor in the development of wind energy resources. In the case of building-mounted wind turbines (BMWTs), in addition to the usual airborne sound there is the potential for occupants to be affected by structure-borne sound and vibration transmitted through the building structure. Usual methods for prediction and evaluation of noise from large and small WTs are not applicable to noise of this type. This letter describes an investigation aiming to derive a methodology for prediction of structure-borne sound and vibration inside attached dwellings. Jointly funded by three UK government departments, the work was motivated by a desire to stimulate renewable energy generation by the removal of planning restrictions where possible. A method for characterizing BMWTs as sources of structure-borne sound was first developed during a field survey of two small wind turbines under variable wind conditions. The 'source strength' was established as a function of rotor speed although a general relationship to wind speed could not be established. The influence of turbulence was also investigated. The prediction methodology, which also accounts for the sound transmission properties of the mast and supporting building, was verified in a field survey of existing installations. Significant differences in behavior and subjective character were noted between the airborne and structure-borne noise from BMWTs.

Keywords: building-mounted wind turbines, structure-borne noise, permitted development

1. Introduction

Noise continues to be a significant factor in the development of wind energy resources. In the case of building-mounted wind turbines (BMWTs) (see [1]), in addition to the usual airborne sound there is the potential for occupants to be affected by structure-borne sound and vibration transmitted through the building structure. Usual methods for prediction and evaluation of noise from large and small wind turbines are not applicable to noise of this type but it could be a significant factor in obtaining planning permission for BMWTs.

In the UK, several renewable technologies have been classified as 'permitted development' whereby installation is allowed without planning permission. To date no such rights have been granted for BMWTs as a result of the uncertainty about possible impacts on residents of structure-borne sound and vibration [2]. Within this context a research project was funded by three UK government departments with the aims of (a) proposing and testing a method for the characterization of BMWTs as sources of structure-borne sound and vibration, and (b) developing and testing a method of predicting structure-borne sound and vibration in a wide variety of installations in the UK. A full report of the project is provided in [3–5].

Sound from BMWTs can be categorized as either airborne or structure-borne sound. The former category consists of sound transmitted through the air which may enter the building, typically, through a façade. It occurs to a greater or lesser extent from all wind turbines, including pole-mounted and free-standing machines. Since there are established methods of rating and assessment for airborne sound [6, 7] it will not

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be considered further in this letter. Structure-borne sound on the other hand, consists of sound which starts as vibration and is transmitted through the building structure. In practice it only occurs in cases where there is a structural connection between the wind turbine and the building and so is particular to BMWTs. In addition, the same mechanisms of vibration generation and transmission may potentially result in other perceptible phenomena within the building, namely tactile ('feelable') vibration and rattling of fixtures and fittings. These latter two categories were considered in the project but were not found to be significant for the range of installations investigated. They will not therefore be considered further in this letter, although they should perhaps not be discounted *per se* in other installations. Therefore, the remainder of the letter will focus on structure-borne sound.

Three separate factors influence the noise and vibration levels in buildings due to an attached BMWT: (a) the BMWT itself which acts as the source of sound and vibration (b) the mounting system including pole, brackets, stand etc, and (c) the building which acts to transmit the sound and vibration to the occupants.

The type of building is expected to have a significant influence on the levels of sound and vibration internally. For example masonry, timber and steel frame constructions all have widely differing structural dynamic properties and will affect the transmission in different ways. Therefore, the same WT, hypothetically operating under identical wind conditions but attached to a different building, is expected to cause differing levels of sound and vibration. Because of the influence of the building a BMWT cannot be characterized independently as a source of structure-borne sound and vibration simply by measuring sound or vibration levels in the building.

2. Small wind turbines as sources of structure-borne sound

In this section we first briefly review the mechanisms of vibration generation and then describe the method used for characterization of the BMWT as a source of structure-borne sound.

2.1. Generating mechanisms of structure-borne sound

Although studies of vibration generation within a BMWT have not been widely reported, the mechanisms are clearly linked to those of airborne sound generation which are reasonably well understood. The mechanisms that produce aerodynamic noise are turbulent boundary layer trailing edge noise, separated flow noise, laminar boundary layer vortex shedding noise, tip vortex formation noise, trailing edge bluntness vortex shedding noise and turbulent inflow noise [8]. These mechanisms are expected to scale with Mach number, i.e. their strength increases with the speed of the flow relative to the blades. Inflow turbulence also increases noise levels [8]. As with aerodynamic noise it is known that vibration also increases with both wind speed and turbulence [9]. Generally, aerodynamic noise is generated when fluctuating aerodynamic forces act on the air surrounding the blades; the same forces, or more correctly the reaction to these same forces, will also tend to generate structure-borne sound by acting back through the blades so as to excite the supporting structure. Vibration may also arise due to mechanical excitation inside gear boxes and magnetic forces in the generator. Structure-borne sound and vibration has not previously been widely investigated but is considered in [10].

2.2. Source characterization

In order to provide a prediction method it is necessary to characterize the BMWT as a source of structure-borne sound. By characterization is meant the acquisition of data to quantify the inherent source strength of the BMWT. In terms of airborne sound, wind turbines are generally characterized either in terms of the sound power level [6] or the sound pressure level [7] at a given distance under free field sound propagation conditions. Characterization of structure-borne sound sources is however more complicated: the only standard approaches require particular mounting conditions which cannot be realized for wind turbines in either case.

The need for realistic operating conditions suggests an *in situ* measurement approach, but as mentioned in section 1, whilst it is possible to measure sound and vibration levels in a typical installation, the measured levels do not intrinsically characterize the source since they are in part determined by the supporting structure (mast, building etc). The important practical implication is that measurements made on one installation are not transferable to another, even for the same BMWT under the same operating conditions.

These conflicting requirements have been resolved in the current project by adopting an approach known as the '*in situ* blocked force' approach [11]. It is based on vibration levels measured *in situ*, however, the measured levels are adjusted so as to 'remove' the properties of the installation (mast, and building) leaving an intrinsic characterization of the source in terms of 'blocked forces'. The physical meaning of the blocked forces is explained in [11] but for the purposes of this letter they can be taken as the hypothetical dynamic forces that a given BMWT would apply to a perfectly rigid base when operating under given conditions. The higher the blocked force, the greater the excitation of the building.

The validity of the measurement approach was confirmed prior to field measurements by testing in the laboratory. A mock up wind turbine was attached via a typical wall mounting to the wall of a reverberation chamber. An electric motor, rather than a BMWT, was used as a vibration source so that its operation could be accurately reproduced for validation measurements. Measurements from two separate mounting configurations confirmed that whilst the vibration levels in the wall varied significantly depending on mast length, the blocked forces were the same in both cases thus confirming the independence and the transferability of the blocked force data. It also became evident that the mechanisms of generation and transmission are complex and that it is necessary to retain five separate blocked forces in order to fully describe the source. These tests are described in more detail in [4].

Figure 1. Photograph of BMWT mounted on a 'flat roof' mounting system at the test site, also showing some of the accelerometers.

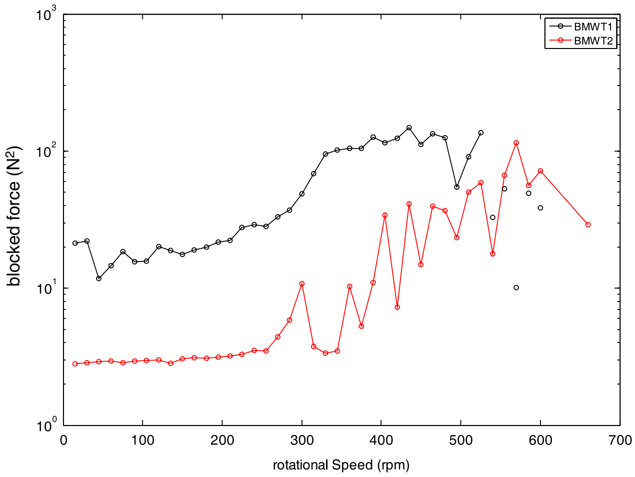

Figure 2. Blocked force (source strength) taking into account the x, y and z directions in the third octave bands 160–315 Hz plotted against rotational speed. Black circles not joined by a line are indicative results for MWT1 based on the few samples that were available for those speeds.

2.3. Measurement and analysis

Having validated the approach in the laboratory, field tests on two models of BMWT (1.7 and 1.1 m diameter) in actual operation were conducted over a period of about five months. The units were pole mounted at a height of 5 m on a flat, open site as shown in figure 1. Accelerometers (vibration sensors) were attached to the mast at 11 points. A pole-mounted sonic anemometer, also at 5 m height and located 10 m from the BMWT monitored tri-axial wind speed and turbulence intensity. Rotational speed of the BMWT was also monitored using a tachometer made from a small reed switch triggered by a magnet attached to one of the blades. Rotation of the blades therefore triggered data capture such that data was streamed in real time to a 1 Tbyte hard disk.

In a separate set of tests, with the BMWT static, the dynamic properties of the mast were measured. These 'frequency response function' tests involve tapping the mast with a special instrumented hammer at the accelerometer locations and measuring the resulting vibration at the top of the mast. The blocked forces could then be calculated by correcting the measured vibration levels for the mast properties. Note that when using this approach the turbines do not have to be attached to a building in order to generate data suitable for characterization.

It is conventional to provide airborne sound of wind turbines as a function of wind speed or power. The structure-borne sound source strength can also be expected to vary with wind conditions. However, as discussed later, it was not easy to correlate source strength to wind speed, largely because of the rapid fluctuations in rotor speed which are a feature of the small machines under test. It also proved surprisingly difficult to measure power with enough resolution to capture these rapid speed variations. A way round these issues was to relate the blocked forces to rotor speed.

The entire time history of the vibration signal was split into 4 s windows from each of which a spectrum was calculated. A 50% overlap was used so that a spectrum was produced every 2 s. Although the rotor speed was varying continuously, the 4 s window was sufficiently short that one could generally identify a dominant rotor speed for each window. This enabled the spectra to be sorted into bins corresponding to the dominant rotor speed for each window. It was then possible to express the average blocked force spectrum as a function of rotor speed.

The blocked forces obtained for the two models of BMWT are shown in figure 2. In order to show the trend with rotor speed, the spectrum has been averaged across the most significant frequency bands. From figure 2, the structure-borne sound source strength first increases and then levels off or even decreases as speed increases. This behavior is fundamentally different to that of the (airborne) sound power of wind turbines, which tends to increase monotonically with wind speed. The trend is probably due to a resonance phenomenon similar to that observed with the familiar case of washing machines undergoing a ramp up in speed where vibration may be seen to reach a maximum at a given speed with a subsequent decrease. The higher values of blocked force for BMWT1 are at least in part due to its larger size (600 W nominal power as opposed to 400 W).

3. Effect of wind speed and turbulence

The fact that potential BMWT sites are characterized in terms of wind speed rather than rotor speed makes it important to relate source strength to wind speed if possible. In section 3.1 we seek such a relationship via the intermediate quantity of rotational speed (see figure 3). The influence of turbulence on structure-borne sound generation will be discussed in section 3.2.

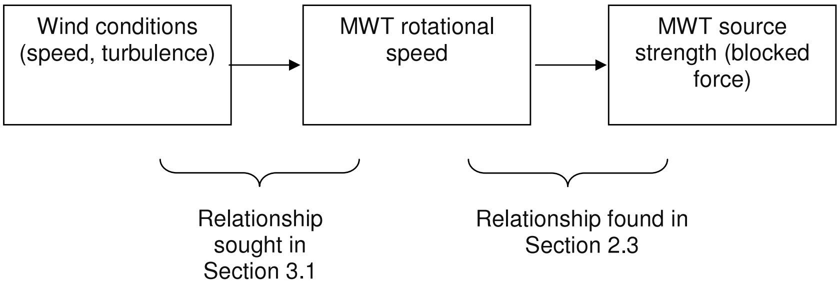

Figure 3. Relating source strength to wind speed via the intermediary quantity of rotational speed.

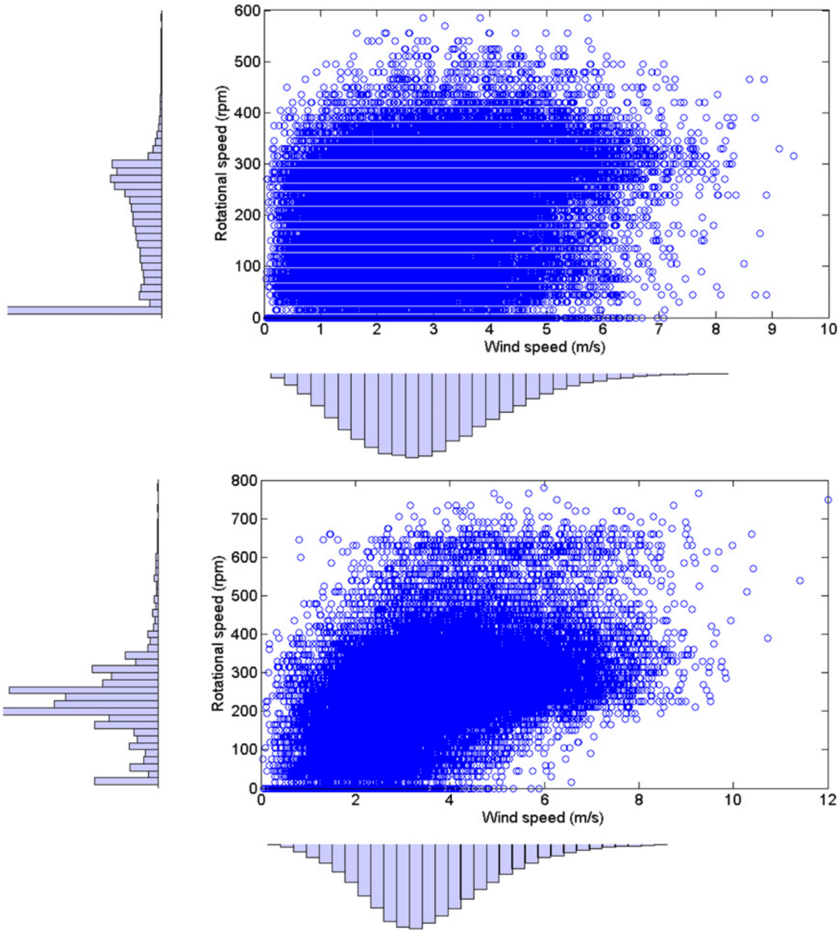

Figure 4. Rotational speed versus wind speed for 4 s samples also showing marginal probability distributions. Top: BMWT1. Lower: BMWT2.

3.1. Relationship of rotor speed to wind speed

Shown in figure 4 is a scatter plot of about 65 thousand observations of wind speed and rotor speed obtained for both models of BMWT. For consistency with the source strength data discussed in section 2.3 the speed data was averaged over 4 s with a 50% overlap so that an observation was made every 2 s. The data therefore represents about 36 h of data for each machine, although the actual measurement period was longer, including idle periods during which no data was captured. It is seen that the marginal distribution of wind speeds, shown beneath the x axis, indicates a Weibull distribution, typical for wind speed data. On the other hand, the rotational speed of the BMWT (next to the y axis) does not conform to any standard distribution (note that. although most idle periods were rejected by the triggering process, the y axis indicates a number of observations at 0 rpm).

In order to reduce the scatter seen in figure 4 the averaging time was increased in steps. A reasonable curve fit was obtained for 5 and 10 min averages (typical periods for analysis of wind data). Examples of the resulting plots are shown in figure 5 which bear some resemblance to published curves for BMWTs of this type. Given the relationship in figure 5 it is then tempting to try to reinterpret figure 2 so as to provide blocked forces as a function of wind speed. However, in

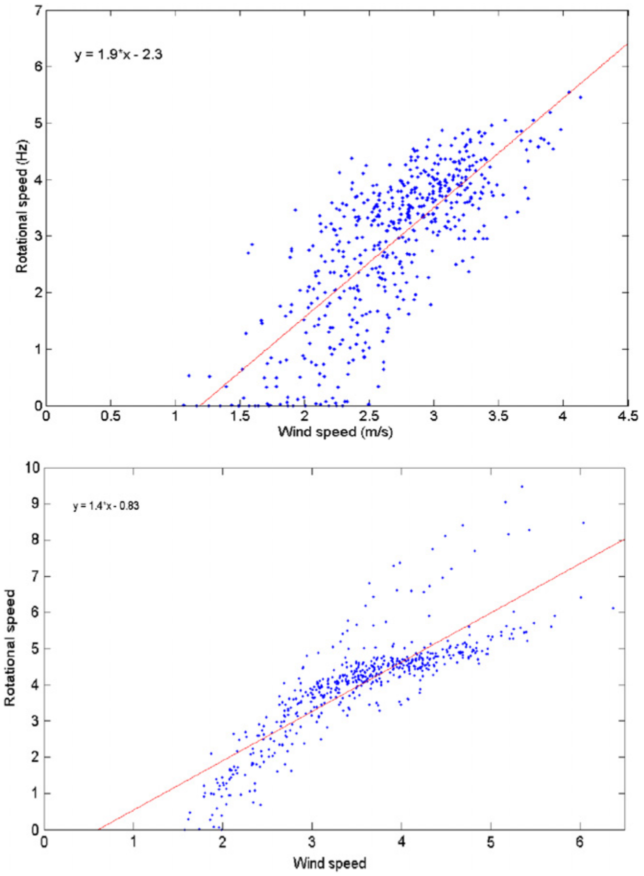

Figure 5. Rotational speed versus wind speed for 5 min samples. Above: BMWT1. Below: BMWT2.

order to generate figure 2 it was necessary to analyze data in relatively short windows (4 s) so as to minimize the variation in rotational speed within the window length. In contrast, significantly longer windows (5 min) were required in order to find a stable relationship between wind speed and rotor speed. Since from experience, the rotor speed is expected to vary significantly during any 5 min period it is not valid to apply the 5 min regression line shown in figure 5 to the *x* axis of figure 2. Indeed, since the relationship between source strength and rotor speed is not linear, this approach would not yield reliable estimates of the 5 min averaged source strength. The relationships shown in figures 2 and 5 cannot therefore be combined.

Therefore, whilst the source strength data shown figure 2 should apply generally to the particular model of BMWT irrespective of the actual wind conditions on site, it is a more complicated matter to provide source strength data in terms of wind speed. Indeed, it seems likely that the relationship between wind speed and rotor speed depends on terrain roughness and is therefore site-specific. In [4] the wind speed and source strength data from the test site has been analyzed so as to provide statistical measures of noise level as a function of wind speed but this analysis will not be repeated here.

3.2. Influence of turbulence

It was noted in section 2.1 that aerodynamic noise can increase with inflow turbulence so it is feasible that structure-borne sound source strength could be similarly affected. Since sites for BMWTs are, by definition, in close proximity to buildings it was of concern to ensure that the influence of turbulence on source strength was adequately represented. To this end, simultaneous tri-axial wind speed and turbulence measurements were made on the test site (see figure 1) and on the roof of an eight-story tower block in an urban area approximately 14 km away.

Wind speeds at both sites were found to conform to a Weibull distribution which can be described by the scale factor, c, related to the average wind speed and the shape factor, k, related to terrain roughness. The values at the flat test site were: $k = 2.9$ m s^{-1}, $c = 1.5$ which are slightly lower than average. The corresponding values at the rooftop site $k = 2.7$ m s^{-1}, $c = 1.4$.

The turbulence intensity measured at both sites is shown in figure 6 and was significantly higher at the rooftop than at the flat test site. Generally, this would be expected because of the higher terrain roughness in an urban area. A detailed analysis of wind direction also showed the presence of 'shadows' in certain directions, indicative of screening by nearby objects, at the rooftop site. It is also clear from figure 6 that the turbulence intensity is negatively correlated with wind speed. In part this is due to the definition of turbulence intensity as the standard

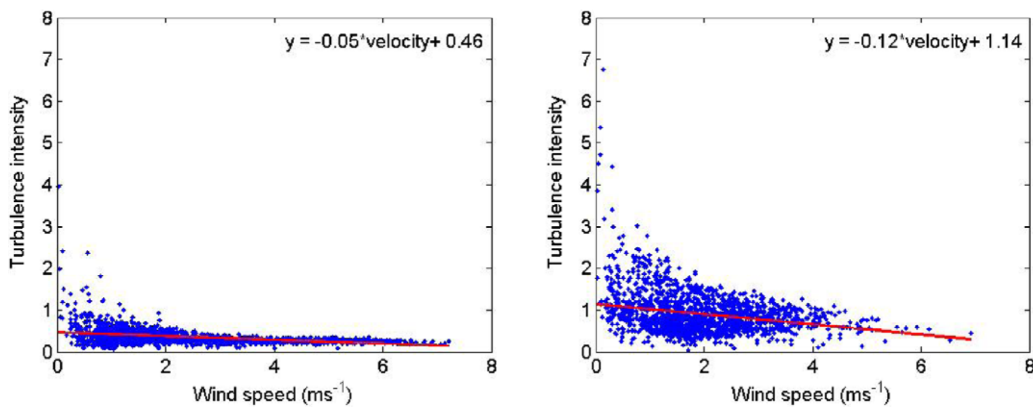

Figure 6. Correlation between wind speed and turbulence. Left: test site (industrial). Right: Allerton (multi-story urban rooftop).

deviation divided by mean wind speed. In an attempt to see a clearer trend, an alternative, non-standard measure, the rate of change of wind velocity, was also evaluated. The results [4] were not easy to interpret but did not give any indication of a strong effect of the rate of change of velocity on the rotor speed.

At this point a difference in the character of airborne and structure-borne noise emission from the BMWTs is noted: the former is often described as a 'swish' and has a 'broadband' spectrum indicative of random forces such as might be caused by turbulent airflow around the blades. The structure-borne sound on the other hand can be described predominantly as a 'whine', suggesting that the dominant generating mechanisms are periodic and linked to blade and generator rotation. The implication is that random forces, such as might be caused by turbulent airflow, do not play a dominant role in the structure-borne sound generation.

However, the effect of turbulence is complicated and will be expected to depend on its length scale. For example, it seems likely that large scale turbulence could be seen by the BMWT as gusts which may cause a temporary increase in rotor speed and structure-borne sound. On the other hand, small scale turbulence may reduce efficiency resulting in lower rotor speeds and lower levels of sound. Therefore in general, as is often the case, the role of turbulence is not fully understood.

4. Prediction methodology

Sections 2 and 3 dealt with the first aim of the project relating to source characterization. In what follows we describe the prediction method which was developed in response to the second aim.

4.1. Influence of mast and building

In order to predict structure-borne sound it is necessary to take account of, in addition to the source, the transmission through the mast and building.

The influence of the mast was characterized by its 'transmissibility' which quantifies the ratio of forces at the top of the mast, the point at which the blocked forces are defined, to those at the base where it connects to the wall. These properties were obtained by laboratory measurement of typical wall mounting systems with varying lengths of pole. The measurements were supported by results from simple dynamic models. It was determined that the mast properties may have a significant effect on the transmission of structure-borne sound. The influence is mostly due to resonances of the free length of the pole which may increase transmission when a multiple of rotor speed coincides with the resonance frequency.

Both building construction and layout may also influence transmission. Unfortunately, information on the relevant properties of buildings is not generally available and modeling techniques are not sufficiently advanced to be able to provide the required data. Therefore, a field survey was conducted in order to obtain the needed information. It was necessary to limit the scope of the survey to masonry constructions (a) because it is the most common building type in the UK and (b) because the acoustic properties of other constructions, timber and steel frame, would be expected to be much more variable and therefore difficult to generalize.

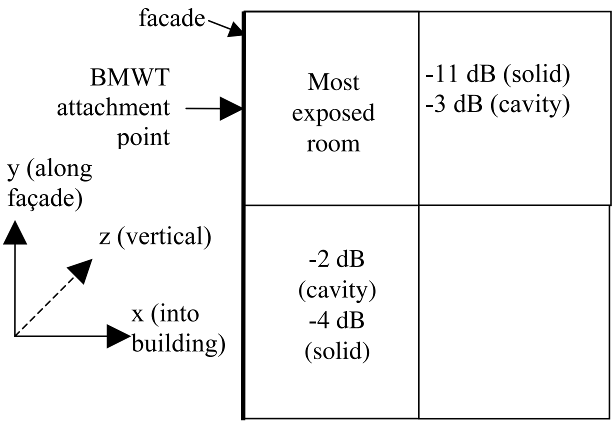

Figure 7. Summary of correction factors for remote rooms for a wall-mounted BMWT. The numbers indicate the approximate reductions in sound pressure level for rooms one removed from the most exposed room either along the façade or into the building. Reductions along the façade can be expected to apply both horizontally and vertically.

In the survey, frequency response functions were measured by striking the building with a special instrumented sledgehammer at a point representative of a BMWT attachment point, and recording the resulting sound pulse in a room representing the receiver room. It was not necessary that a BMWT be attached in order to obtain these results. The results indicated that for the same source, the sound levels in the most exposed room (immediately behind the attachment point) would be expected to be about 10 dB lower on average for cavity constructions than for solid masonry constructions. Individual results could however be variable because construction details can vary widely, especially for cavity masonry and a larger scale investigation would be required to provide statistically significant results.

The influence of building layout, particularly on the location of the receiver room in relation to the most exposed room, is summarized in figure 7. These indicate that for rooms one removed from the most exposed room, either vertically or horizontally along the BMWT-supporting façade, the levels would be expected to be 2 dB or 4 dB lower than those in the most exposed room for cavity and solid brick respectively. These attenuations are relatively small and would not be particularly noticeable subjectively. Moving into the building, away from the supporting façade, higher attenuation would be expected for solid masonry, but that for cavity brick is still relatively small. Generally then, there is surprisingly little benefit for rooms remote from the attachment point especially for cavity walls.

4.2. Prediction approach

The aim was to derive a simple prediction method in order to make it as widely applicable as possible. It has been seen in the previous sections that the characterization method

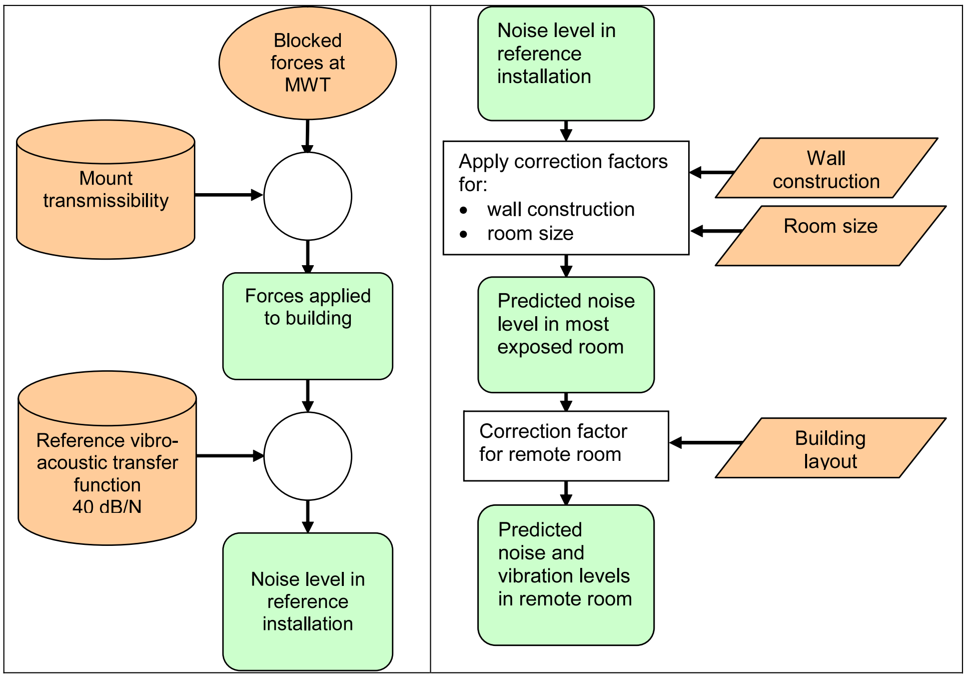

Figure 8. Flow chart for prediction of noise levels as a function of rotor speed. Left: prediction of sound levels in the reference installation. Right: correction for construction type, room size and building layout.

requires sophisticated measurement and analysis and could not be carried out by a non-specialist. In order to simplify the prediction from that point on, the concept of a reference installation was introduced. The reference installation is a hypothetical installation consisting of a BMWT with a mast of specified length attached to the solid masonry wall of a building and with a receiver room immediately behind the point of attachment of 50 m^3 volume and typical living room furnishings. Defining the mast and building in this way allows us to express results for a given BMWT in terms of the sound pressure level in the reference installation, which is easier to interpret than the blocked forces. Furthermore, it allows simple adjustments to be made to the levels to account for cavity constructions and for different building layouts by using the results of section 4.1. Similar corrections can be applied for room volume.

A flow diagram for the prediction method is shown in figure 8. The first part involves calculation of levels in the reference installation and requires specialist expertise to implement. Once the reference installation noise levels are available however, the second part of the prediction, where levels can be adjusted for building construction, layout and room volume, could be conducted by a non-specialist. Figure 9 illustrates the reference installation noise levels which serve as input to the simplified prediction method. Note that the levels, particularly for BMWT1, depend quite strongly on the length of the mast. It can also be observed that the levels do not continue to increase as the rotor speed increases but level off above about 300 rpm.

The simplified prediction method (on the right of figure 8) is described in full in [4, 5].

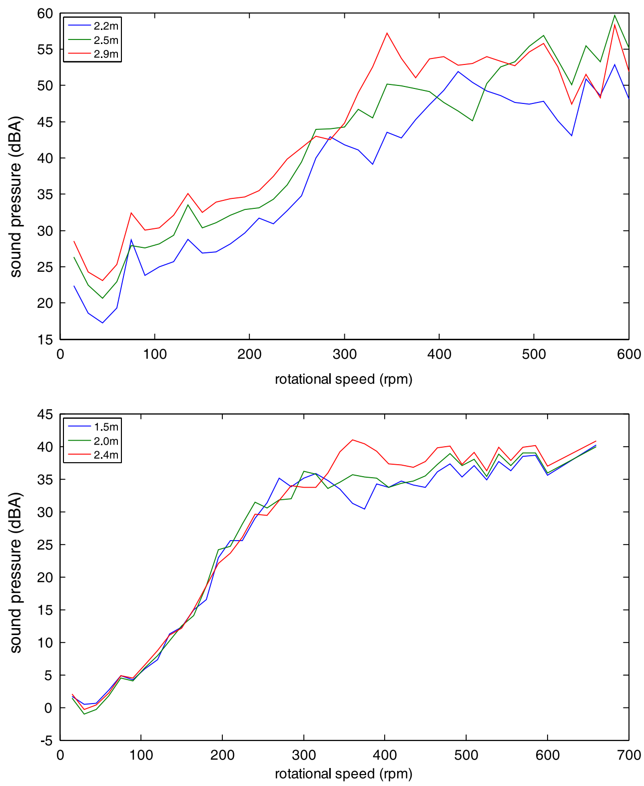

Figure 9. Sound pressure in the reference installation for three different mast lengths. Upper: BMWT1. Lower: BMWT2.

5. Field survey of small wind installations

A field survey of BMWT installations was carried out, partly so as to provide a means of checking the prediction method

Table 1. Summary of noise and vibration levels from case studies.

Case study	MWT	Construction	Mounting	Maximum measured level (L_{Aeq}) (Period)	Max rotational speed (rpm)
1	BMWT1	Solid brick	Wall	38 dB(A) (5 min)	402
2	BMWT1	Cavity brick	Wall (figure 10)	45 dB(A) (1 min)	378
3	BMWT1	Concrete roof	Flat roof (see figure 1)	45 dB(A) (5 min)	435
4	BMWT2	Cavity brick	Wall (figure 11)	29 dB(A) (5 min)	360

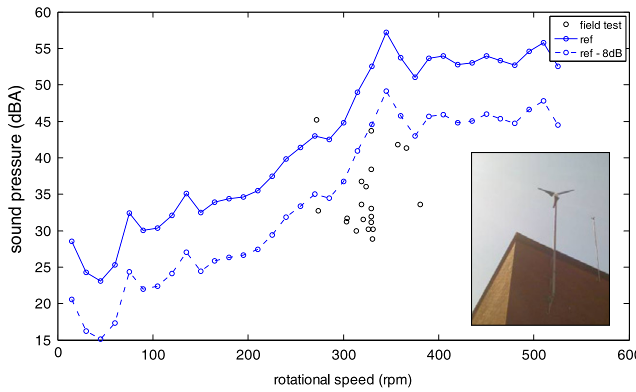

Figure 10. Case study 2: snapshot L_{Aeq} versus rotational speed. Solid line: calculated noise level in reference building. Dotted line: reference building noise level −8 dB. Inset: photo of test site showing wall-mounted BMWT.

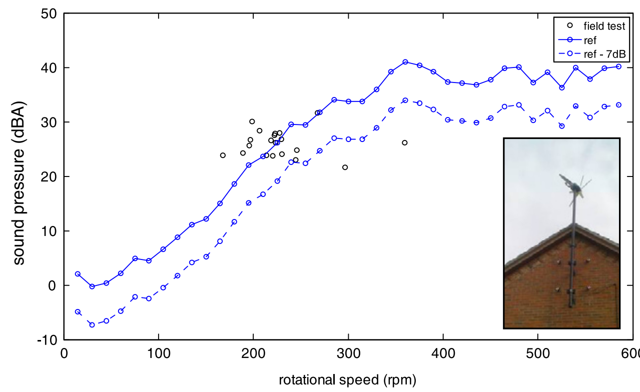

Figure 11. Case study 4: snapshot L_{Aeq} versus rotational speed: solid line: calculated noise level in reference building. Dotted line: reference building noise level −7 dB. Inset: photo of test site showing wall-mounted BMWT.

and partly to collect information about levels of structure-borne sound in real installations. Four case studies were evaluated, including examples of both of the models of BMWT studied, and for a variety of construction types. Results are summarized in table 1. Ideally, 5 min averaged sound levels would have been measured ($L_{\mathrm{Aeq,5\ min}}$) for comparison with criteria for airborne noise [2], but due to background noise a shorter measurement period was sometimes necessary.

The measured noise levels due to the BMWT ranged from 29 to 45 dB averaged over 5 min ($L_{\mathrm{Aeq,5\ min}}$) or as close as could be obtained. The levels for BMWT2 were lower than those for BMWT1 which is probably due, at least in part, to the smaller capacity of the latter. Subjectively, the BMWT noise was audible as a 'whine' in case studies 1 and 2 and was just audible in case study 4. Case study 3 was the only roof-mounted case and showed the highest noise and vibration levels. However, the high levels in this case are believed to have been strongly influenced by the design of the flat roof mounting system in which unsecured ballast was able to vibrate when the wind turbine was running.

Shown in figure 10 are the predicted noise levels for case study 2 as a function of rotor speed. The solid curve gives the noise levels in the reference installation (from figure 9). To obtain the dotted line, adjustments were made according to section 4.1: 10 dB was subtracted for cavity walls and 2 dB added for room volume. The dots represent snapshot measurements obtained at times when background noise levels were sufficiently low. There is a reasonable agreement between the measured and predicted results. Figure 11 shows results in a similar format for case study 4. Again, there is reasonable agreement between measurement and prediction, although levels are slightly under-predicted.

Neither perceptible vibration nor rattling of fixtures and fittings was reported by any of the residents and measurements showed the levels to be below perception thresholds on the whole. However, it is feasible that perceptible vibration could occur in other situations.

6. Conclusions

Structure-borne sound is potentially of concern for building-mounted wind turbines (BMWTs). Its generating mechanisms are linked to those of airborne sound generation but different treatment is required for evaluation and prediction. A method for characterization of a BMWT as a source of structure-borne sound and vibration has been proposed and tested. It is based on measurements made *in situ* on a normally operating BMWT, but a correction is made so that the data obtained is independent of the supporting structure. From a series of field tests on two types of BMWT blocked force data has been obtained as a function of rotor speed. Ideally, the data would be presented as a function of wind speed but a suitable relationship could not be found, largely due to the rapid fluctuations of blade speed which typically occur with the small machines studied. Whilst turbulent inflow can increase levels of airborne noise it seems unlikely that turbulence will significantly increase levels of structure-borne noise for BMWTs.

A two-stage prediction method has been developed and tested. The first stage involves characterization of the BMWT and calculation of noise levels in a hypothetical 'reference installation'. The second stage involves adjustment of the levels for particular building constructions and layouts. The first phase requires specialist knowledge but the second stage is suitable for non-specialists.

Whilst airborne noise from (mostly large) wind turbines has been widely studied, the understanding gained may not tell us much about structure-borne noise from smaller machines since there are significant differences in behavior and the subjective character of the noise. First, the structure-borne sound has the character of a 'whine' which in psycho-acoustic terms is quite different to the familiar blade 'swish' from airborne sound. Furthermore, small machines run faster and their speed changes more rapidly than larger machines so that the structure-borne sound varies in pitch more or less continuously. Moreover, whilst for airborne sound the highest levels will in general occur at the highest wind speeds, the maximum structure-borne sound is likely to occur at a particular running speed that coincides with structural resonances.

Structure-borne noise levels of up to 45 dB ($L_{\mathrm{Aeq,5\ min}}$) were recorded in some cases for BMWT2 although those from BMWT2 (a smaller machine) were lower. Noise acceptance criteria often differ across nations or regions and no specific criteria relating to structure-borne sound from BMWTs exist in the UK. However, based on generic guidance such as given by WHO [12], we might expect sound levels at the lower end of those recorded, broadly speaking, to meet with acceptance and those at the higher end to be judged unacceptable. Therefore, it will be necessary to consider new installations on a case by case basis.

There is scope for noise reduction through design modifications of the turbine, their mounting systems and with the use of certain installation techniques.

Acknowledgments

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