



University of Salford
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Defra NANR244

Noise and vibration from building-mounted micro wind turbines

Part 1: **Review and proposed methodology**

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Executive Summary

- 1 The aims of the project are to propose and test a method for the characterisation of micro wind turbines (MWTs) as sources of structure-borne sound and vibration and secondly to develop a method of predicting structure-borne sound and vibration in a wide variety of installations in the UK.
- 2 This report is the first of three reports for the project. It was originally presented shortly after the start of the project, and its aim is to review available methods and to propose a suitable approach for the prediction methodology. To do this it has proved convenient to consider separate elements of the problem:
 - * The generation of structure-borne sound and vibration by the MWT
 - * The attenuation offered by the mounting system
 - * The transmission of sound and vibration through the building to receiver locations in attached neighbouring dwellings.
- 3 A number of trials have previously been conducted on micro-wind installations but these have focused on power generation rather than noise and vibration.
- 4 A study of the noise and vibration from several roof-mounted micro-turbines (Ashenden House, Southwark) concluded that urban installations should not generate noise and vibration complaints. However, we have argued that this conclusion may not apply generally to MWTs and this argument is supported by experience from the Warwick Wind Trials.
- 5 During the Warwick Wind Trials some residents complained about noise and vibration from some roof-mounted MWT installations. The Environmental Health Department declared that the installation was causing a statutory nuisance and a number of turbines consequently had to be de-commissioned. Clearly, this may have implications for permitted development rights.
- 6 In a survey of attitudes conducted as part of the Warwick Wind Trials, 11 of 25 people from a block of flats with roof-mounted MWT installations expressed dissatisfaction at the presence of turbines on their buildings. Of those who expressed dissatisfaction, 10 cited noise (and vibration) as the reason.
- 7 There are three types of domestic MWTs produced in the UK. For the purposes of this report we have referred to the turbines as Turbine 1, 2 and 3. Turbines 1 and 2 can be wall or roof mounted, and Turbine 3 is wall mounted.

- 8 Cavity and solid brick constructions and flat roofs were the most common building types encountered in the Warwick Wind Trials and also account for the majority of dwellings within existing housing stock in the UK. We therefore propose to include these building types in the study. It is not possible to make general remarks about the vibration and sound transmitting properties of construction types other than masonry, timber frame, steel frame and SIPs, except to say that a strong dependence on the details of the attachment points of a MWT is expected.
- 9 Structure borne sound sources can be characterised independently using an in-situ blocked force measurement approach. The approach is feasible for the characterisation of MWTs. Other methods exist but cannot be applied to MWTs or else the data is of a less useable form. Implementation of this method will be challenging; it will be necessary to measure multiple channels of vibration data whilst the MWT is in normal operation, but this can be achieved with modern equipment.
- 10 Testing is proposed for characterisation of test MWTs as sources of structure-borne sound and vibration. Measurements will be required for a range of wind conditions to create a multidimensional database. It will also be necessary to measure wind speed and turbulence simultaneously.
- 11 A standard has recently become available (EN12354-5) for the prediction of sound from structure-borne sound sources in buildings. This provides a potential framework for the prediction methodology. The approach has not to date been tested in its entirety. However, an important element of the method, relating to the transmission through the building has been widely researched over the last decade. This aspect of the method is fairly widely accepted internationally and reasonable accuracy has been obtained in field trials.
- 12 An alternative to the energy approach of EN12354 is to use a transfer function approach which might be more suitable for low frequency prediction.
- 13 The source can be characterised by the ‘characteristic power’ or by the ‘blocked force’. Both quantities can be obtained from the proposed in situ blocked force measurement method on the test MWTs. Both are expected to vary with wind speed and possibly with turbulence and wind direction.

- 14 Some of the assumptions in EN12354 mean that predictions at very low frequencies may be suspect. The assumptions are similar to those used in most building acoustics standards which do not work well for very low frequencies. Whether this will be a problem in this project depends on the frequency content of the MWT in operation which will not be known until the first measurements are obtained on the test installations.
- 15 Criteria for acceptable levels of structure-borne sound, tactile (feelable) vibration, building damage and rattling of fixtures and fittings have been reviewed. No specific criteria are available for MWTs but other existing criteria can be adapted.
 - * Current standards in the UK for tactile vibration assess the possibility of adverse comment on the basis of a vibration dose value (VDV) over 8 hours (night) or 16 hours (day).
 - * There are standards for assessing potential building damage in terms of a maximum 'peak particle velocity' (ppv): we propose to measure or predict the ppv at the point of attachment of the MWT.
 - * To assess the likelihood of rattling, a maximum acceleration level in walls is proposed.
 - * For structure-borne sound we propose that 5 minute averaged, 'A' weighted sound level ($L_{Aeq, 5 \text{ minutes}}$) at a position near the centre of the room would be the most appropriate indicator.
- 16 A prediction methodology has been outlined.
 - * The MWT will be characterised using the Characteristic Power or blocked force obtained using the in situ blocked force method
 - * The mounting attenuation will be characterised using a coupling term as defined in EN12354-5 or by its transmissibility.
 - * Transmission through the building will be characterised through sets of measured transfer functions for typical dwellings.
- 17 Consideration has been given as to how the outputs of the prediction methodology can be made as simple as possible.

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1 Introduction

The aims of this project are to “*research the quantification of vibration from a micro turbine, and to develop a method of prediction of vibration and structure borne noise in a wide variety of installations in the UK*” (quoted from the NANR244 project specification, June 2009).

The outcomes of the project are described in two reports:

Part 1: Review and proposed methodology;

Part 2: Development of prediction method;

This report is the first: its aim is to review available methods and to propose a suitable prediction methodology. In order to do this it has proved convenient to consider separate elements of the problem:

- The generation of structure-borne sound and vibration by the building-mounted micro wind turbine (MWT)
- The attenuation offered by the mounting system
- The transmission of sound and vibration through the building to receiver locations in neighbouring attached dwellings.

It will be seen that the problem is a complex one and that standardised approaches do not exist covering all aspects.

1.1 Outline of this report

In Chapter 2 ‘Building-mounted micro-turbines – state of the art’, we look at the studies of micro wind installations conducted to date, the types of turbines available, their reliability and the range of installations from the Warwick Wind Trials. We also describe noise complaints received and the results from a survey of attitudes towards MWTs made during the Warwick Wind Trials. Finally, we consider UK housing stock and propose a range of building types to be investigated during the study.

In Chapter 3 ‘Characterisation of structure-borne sound sources’ we review the available methods of characterising sources of structure-borne sound and vibration. The considerable practical difficulties of characterising MWTs as structure-borne sound sources are described and a way forward is proposed.

In Chapter 4 ‘Transmission of Structure-borne sound’ we review methods for

prediction of transmission of sound and vibration through buildings, with particular emphasis on a new standard, EN12354-5: 2009 which provides a possible framework for the prediction methodology. In particular, the reliability of predictions is evaluated.

In Chapter 5 ‘Relevant noise and vibration criteria’ criteria for evaluation of the acceptability or otherwise of structure-borne sound are reviewed. This is necessary to ensure that measurements made during the project, as well as the prediction method, provide outputs that are compatible with accepted criteria.

Chapter 6 ‘Evaluation of wind conditions’ assesses the influence of wind speed and turbulence on the generation of noise and vibration from wind turbines. The range of wind conditions likely to be encountered in UK sites is also evaluated.

In Chapter 7 ‘Proposed prediction methodology’ we present an outline of the approach proposed for the prediction methodology and the measurements required to obtain the necessary data. We also consider the possible form of the outputs from the prediction methodology: despite the complexity of the problem we put forward some ideas as to how the results might be presented in a relatively simple form.

2 Building-mounted micro-turbines – state of the art

In this section we will look at the studies conducted to date, the types of turbines available, their reliability and the range of installations from the Warwick Wind Trials. We also describe noise complaints received and the results from a survey of attitudes towards MWTs made during the Warwick Wind Trials. Finally, we consider UK housing stock and propose a range of building types to be investigated during the study.

2.1 Studies conducted

A number of studies have been undertaken in the last few years to look at the performance of small wind turbines typically sized between 400 W and 6 kW. These studies have considered both building-mounted and freestanding turbines. The focus on these studies has been to look at the performance of these turbines and measure the electrical generation capabilities in differing wind environments. The three main studies are:

- the Warwick Wind Trials in which the performance of 23 wind installations was measured in a mix of urban and rural sites over a 1 year period;
- the Energy Savings Trust wind trial - a larger trial with 57 sites monitored for 12 months;
- Zeeland Small Wind Trial study – which took place at an open field location in Holland and contracted the performance of a number of production turbines.

Other trials were carried out by the Building Research Establishment (BRE). In addition, other isolated tests have been conducted, of note being the trial of two Proven 6 kW turbines by Kirklees Council on their building in Huddersfield. None of the above studies were aimed at noise and vibration, although there were some complaints about noise during the Warwick Wind Trials which will be described later.

In a further study the installation of a Proven 6 kW and Quiet revolution on Ashenden House, Southwark were studied and noise and vibration measurements were made. It was concluded that roof top wind turbines make no difference to vibration comfort levels. Furthermore, it was concluded that Urbines (urban wind turbines) do not acoustically affect the residents nor the urban environment (Dance et al. 2009). However, there was significant masking noise at this highly urban site from general city noise which may not be representative of many other existing and potential sites. Furthermore, the power performance of the test turbines was poor due to relatively low wind speeds, which suggests that on a better site (in terms of power generation)

we might expect greater power generation and with it, higher levels of noise and vibration. In other words, on a different site there may be greater noise generation and less pre-existing background noise to provide masking. For these reasons we do not consider it safe to apply these conclusions generally to building-mounted wind turbines without further investigation. Our caution is corroborated by the fact that complaints about noise from a roof-mounted installation were made, and indeed upheld, during the Warwick Wind Trials (described later).

2.2 Range of installations

We now investigate the range of MWTs available in the UK. The most popular models for the domestic market are outlined below.

Turbine 1

Rated power 0.698 KW
Rated wind speed 11 m/s
Cut-in wind speed 3 m/s
Cut-out wind speed n/a
Maximum wind speed the turbine can withstand 223 Km/h

Specifications:

Rotor weight 16 Kg
Rotor diameter 1.7 m
Swept area 2.27 m²
Height of the mast Variable

Mounting systems available:

Pole
Flat roof
Wall



Turbine 2

Rated power 1,5 KW
Rated wind speed 12 m/s
Cut-in wind speed 4 m/s
Cut-out wind speed 17 m/s
Maximum wind speed the turbine can withstand 223 Km/h

Specifications:

Rotor weight 15 Kg
Rotor diameter 2 m
Swept area 3,14 m²
Height of the mast 5 m

Mounting systems available:

Flat Roof
Wall



Turbine 3

Rated power 0,4 kW
Rated wind speed 16 m/s
Cut-in wind speed 2 m/s
Cut-out wind speed None m/s
Maximum wind speed the turbine can withstand 130 km/h

Specifications:

Nacelle and rotor weight 15 kg
Rotor diameter 1,1 m
Swept area 0,95 m²
Height of the mast Variable m
Maximum rpm 1 200 at rated wind speed

Mounting systems available:

Wall



2.3 Summary of sites used in the Warwick wind trials

As well as the MWT itself, noise and vibration transmission will be strongly affected by the building construction. Therefore, we need to look at the range of installations likely to be encountered in practice and we now summarise the site details from the Warwick Wind Trials. In all these cases, the turbines were purchased through normal channels and installed by the manufacturers.

Table 1: Summary of site details from the Warwick Wind Trials

	Semi	detached	Terrace	Flats	Commercial	Solid wall	Cavity	Flat roof	Steel Frame	Pole mounting
Lillington Road	x					x				
Hill Close Gardens										x
Prince Drive									x	
Birds Hill		x					x			
Eden Court 1				x				x		
Eden Court 2				x				x		
Leicester		x								x
Southern Court 1				x				x		
Southern Court 2				x				x		
Napier					x				x	
Daventry					x		x			
Ashton Court 1				x				x		
Ashton Court 2				x				x		
Daventry County Park		x			x	x				
Fountain Farm	x									x
Misty Farm										x
Tannery Court				x			x			
Nottingham					x				x	
Antrobus Road			x			x				
Summerfield Crescent			x			x				
Park Farm		x								x
Northamptonshire		x			x		x			
Delta Court				x			x			
West Staddon		x				x				
Huddersfield		x			x					
Thatcham					x					x
Totals	2	7	2	8	7	4	5	6	3	6

The building types are summarised in Table 1: there were 4 solid and 4 cavity brick
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walls, 6 flat roof installations and 3 steel frame constructions of which 2 of the latter were for experimental installations on University buildings. Six installations were pole-mounted (i.e. stand alone mast) which are not of interest for structure-borne sound and vibration. From this experience we would expect to include solid and cavity brick, flat roofs and possibly steel frame constructions in the study.

2.4 Turbine reliability

The Warwick Wind Trials project highlighted a number of technical reliability issues with the wind turbines. Reliability problems were encountered with inverters and control boxes that caused capacitor failures in early models. There were also moisture ingress issues through slip rings in the MWTs themselves. Blade failures on two of the manufacturer's wind turbines have been the most serious reliability issue to date due to public safety and one tail failure was also experienced. Many of these failures occurred due to a lack of adequate durability testing and the UK micro wind turbine industry still being in its infancy when the project started. The response from the manufacturers to the reliability issues was good throughout the wind trials.

The responsibility for turbine reliability involves not just the manufacturers but also the installers. One example of this was demonstrated during the trial when there was a structural failure of a gable end wall. Part of the installation procedure is to do a pull test on the fixings to 5kN. Although this procedure ensures that the bolt is bonded sufficiently into the wall and that the brick is securely cemented to the other bricks it does not test the structural strength of the wall itself.

Noise levels were an unexpected issue at three of the trial sites. All of the sites where noise has been an issue involved multiple occupancy buildings. Generally it was not the turbine owners that complained about noise but other residents. Two of these wind turbines are now permanently turned off due to a local environmental health officer stating that the turbines are a statutory noise nuisance. Noise and vibration complaints are discussed in more detail in Section 2.6.

The BWEA Small Wind Turbine Performance and Safety Standard (BWEA 2009) has now set the standard for manufacturers and installers to adhere to. This standard was not in place when the turbines in this trial were installed and suggests that the industry is responding well to issues raised in the field. This standard covers performance testing, acoustic noise testing, durability and safety testing.

2.5 Manufacturer's current practice

In this section we consider manufacturer's current practice with respect to noise and vibration issues.

No data has been published by manufactures detailing any testing carried out on vibration. Discussions with manufactures show that they do not generally follow programmes of testing in the laboratory or in the factory. Rather, they have tended to respond to problems with vibration and noise as and when they arise in the field.

There is some use of vibration isolation techniques and materials on current installations. It is our experience that much of this work has been carried out by trial and error on site rather than through programmes of testing.

Thus, we can be confident that methods or approaches proposed within this project will not cut across manufacturer's existing practice.

2.6 Noise and vibration complaints

This section summarises the noise complaints made through official channels during the Warwick Wind Trials project. Note that a full technical assessment of each case is not available so conclusions should be drawn with caution. The NOABL wind speed estimate for two of the blocks of flats involved was 5.8ms^{-1} at 25m and for the third block was 6.4ms^{-1} at 45m.

An initial complaint was made on October 2007 from a resident living near to the turbines installed on top of three tower blocks. The complainant lived in a semi-detached home along a street within a 100m radius of the turbine installation site. They were woken during the night by a noise coming from the turbines which they described as sounding like a motorbike that could be heard through their double glazed windows. They deemed the noise serious enough to warrant a complaint direct to their local Councillor who they telephoned first thing in the morning after the noise had disturbed their sleep.

The Councillor visited the three blocks on the day the complaint was made to make his own observations. He confirmed the noise was similar to that of a motorbike and could be heard from inside his car with all the windows closed. On returning to his own home he noted that he could still hear the turbines from there, around half a mile away, albeit relatively quietly. The Councillor immediately raised this complaint with

officials at the local District Council and requested that the turbines be disabled as soon as possible and left inoperable until the noise issue was resolved.

The District Council's Environmental Health Officers received no direct formal noise complaint at the time, but the complaint made to the Councillor was treated as such. The Senior Environmental Health Officer (SEHO) for the District Council and his team investigated the noise during both the day and the night through November 2007. These officers reported that noise generated by the turbines was audible from outside the buildings but was not intrusive in the communal areas inside the buildings, even when monitored from the top floors.

The second complaint came on 17th December 2007 and was made directly to the SEHO by a resident living on the top floor of the higher block. The SEHO visited the property that day and was "*amazed at the sheer volume of noise nuisance at which the complainant was being subjected to*". He also stated that his colleague "thought that the complainant was watching a war movie through a surround sound system at full volume", but the TV wasn't even on. The SEHO stated further:

"I have been working in the field of noise and nuisance for 8yrs now, and without doubt, I felt as though the noise witnessed during my visit today, was by far the loudest noise nuisance that I have ever witnessed within this District. It was extremely intrusive and without doubt a 'Statutory Nuisance'. The floor and ceiling were both vibrating violently through the entire duration of our visit."

When asked if the noise he was suffering was this bad on a day-to-day basis, the complainant replied that even when the wind is not as strong, the noise is loud enough to keep him awake at night and stop him from watching the TV at a comfortable listening level. The SEHO declared the noise a statutory nuisance and therefore worthy of a legal abatement notice. He recommended that the turbines should be locked in an inoperable state without delay, and removed as soon as practicable unless a means of attenuating the noise could be installed to prevent nuisance into premises.

The MWTs on all three blocks were turned off and remained switched off from December 2007 following the second complaint until July 2008. During this time the MWTs were upgraded with a new nose cone, new blades and interconnect box with speed control. Prior to this the turbines had a cut out mechanism which would render them inoperable at wind speeds greater than 20 m/s. After the upgrade the new cut out mechanism was limited to a lower wind speed of 10 m/s. The turbines on top of the three blocks were also fitted with a timer switch which was to render them inoperable during the night. This was done to minimise the potential for further noise complaints

whilst still enabling the collection of useful energy generation data.

In October 2008 a third official noise complaint was made, by the same complainant who made the second official complaint. The complainant stated at the time that they had been suffering from turbine noise for the past 4 months. The SEHO again visited the site, this time accompanied by a Chartered EHO (CEHO), also working for Warwick District Council, who stated:

“The noise was very intrusive, aggravated every minute or so by vibration that could be felt in the floor and walls of the living room and bedroom. The noise and vibration was not as evident in the common areas. [The SEHO] came along as he witnessed the nuisance last time when the turbines were cut off - in his opinion the noise is not as bad but bad enough”

The CEHO recommended that the turbines be shut down with immediate effect. He observed that turbines at the two smaller blocks did not appear as bad as those at the higher one, although some noise and vibration was evident. But noise observed on the ground coming from one of the turbines on one of the smaller blocks was very evident, sounding like a prop aircraft revving up for take-off. It should be noted that on the day of his visit, the CEHO observed an additional statutory noise nuisance arising from a skylight over the stairs leading to the top floor at Eden Court which was rattling in the wind. This would have contributed to the overall noise nuisance observed on that day and indeed it seems possible that the source of the noise could even have been mistaken.

The consultants responsible for the installation were disappointed that the turbines were continuing to cause a nuisance despite best efforts to minimise the potential for noise by limiting operational times, lowering the cut out speed and a redesign of the nose cone and blades. Nevertheless all turbines on the three tower blocks were switched off on 1st October 2008 immediately after notification of the third complaint.

In later communications between the Consultants and the CEHO it emerged that the complainant in the higher block suffered noise nuisance even at times when the turbines were switched off (i.e. at night). It was suggested that the noise was caused by the furling movement of the turbines as they turn into the wind. Further investigative work would have been required to establish the true source of the noise nuisance observed at times when the turbines were switched off. It was not clear whether the noise was indeed generated by the turbines or by general wind noise on

the roof around the various static obstructions that are there.

2.7 Opinions relating to MWTs

Encraft conducted a survey of opinions relating to building mounted micro-wind turbines as part of the Warwick Wind Trials project. In total 209 people were surveyed. Of these 89 were members of the public that were stopped on the street in Leamington Spa; 13 were residents living in the area surrounding the turbine installed at Lillington Road in Leamington Spa; 25 were residents living in Eden, Ashton and Southorn Court (high rise apartment blocks); 10 were residents living in the area surrounding the turbine at Hill Close Gardens; and 82 were visitors to the Recycle Warehouse on Princes Drive where another turbine was installed. Of those surveyed, 84% stated that they were not bothered at all by the presence of locally installed building mounted micro-wind turbines. This percentage decreased when only those living close to the turbines were considered.

The following comments were made by those surveyed regarding turbine noise:

“The noise is worst at night although I am getting used to it now and it doesn't really bother me anymore.”

“They are noisy but I like the noise because it is white noise and it helps me sleep.”

“They only seem to be noisy when it is not windy or at night when I am trying to sleep.”

“I can hear the noise but it doesn't bother me.”

“The noise was particularly bad one windy night.” (2 people made this comment)

“They are especially noisy when it is windy.”

“I didn't notice the noise until someone pointed it out to me.”

“There is noise and vibration when it is windy. I can hear it above the noise of the wind. I also think it interferes with my Sky TV signal.” (This resident lived on the top floor of one of the high rise blocks, directly beneath one of the turbines)

“It is noisy in my flat.”

“I've heard other people complain about noise but I can't hear anything in my flat.”

“There is a lot of vibration in my flat and the vibration makes my storage heaters rattle.” (This resident lived on the top floor of one of the high rise blocks, directly beneath one of the turbines)

“The turbine sounds like a motorbike in high winds.”

“I worry that the noise is bad for people living closer to the turbine, but it doesn't bother me.”

From the above we can conclude that there are some noise and vibration issues with existing installations.

2.8 Evaluation of building and construction types to be included

In section 2.3 the building types used for some existing installations were summarised. The aim of this section is to evaluate housing stock in the UK in order to determine building types likely to be used for MWT installation and thereby those to be included in the study.

There are approximately 26.7 million dwellings in the UK. The key sources of information on housing stock are the English House condition survey (2007), the Welsh House Condition Survey (1998), the Scottish House Condition Survey (2008), the Northern Ireland House Conditions Survey (2006) and the General Register Office for Scotland, dwelling numbers estimates (2004).

Table 2: Approximate numbers of dwellings of particular types in England, Scotland and Wales (taken from the House Condition Surveys)

Dwellings in England, Wales and Scotland						
	Terraced	Semi-detached	Detached	Bungalow	Flats and other	all
England						
	6,216,000	6,216,000	3,996,000	2,220,000	3,552,000	22,200,000
%	28	28	18	10	16	100
Wales						
	405,000	387,000	264,000	No information	100,900	1,157,300
%	35	33	23	-	9	100
Scotland						
	Terraced	Semi-detached	Detached	Tenement	Other Flats	all
	504,000	576,000	576,000	432,000	312,000	2,400,000
%	21	24	24	18	13	100

There were approximately 1.2 million dwellings in Wales in 1998. Terraced houses are the most common type of dwelling in Wales making up over a third of stock (35 per cent). Different types of dwelling tended to be built at different times; terraced houses before 1919, semi-detached houses between 1919 and 1944 and detached houses after 1964.

There are approximately 2.4 million dwellings in Scotland. The key sources of information on housing stock in Scotland are the Scottish House Condition Survey, 2008 and the General Register Office for Scotland dwelling estimates of 2004.

A tenement in Scotland is usually thought of as a sandstone or (in Aberdeen) granite building of four or five floors with eight or more flats. But a tenement can also be a modern block of offices or flats, a tower block, a "four in a block" building or a Victorian villa which has been converted into two or more flats.

Table 3: Approximate numbers of dwellings of particular types in Northern Ireland (taken from the House Condition Surveys)

	Bungalow		Terraced House		Semi-Detached House		Detached House		Flat/Apartment		Total	
	No	%	No	%	No	%	No	%	No	%	No	%
Pre 1919	24300	21.3	42620	37.4	7850	6.9	30900	27.2	8140	7.2	113810	100.0
	15.2		18.9		5.6		25.2		14.5		16.1	
1919-1944	8400	11.8	26400	37.2	27560	38.8	7450	10.5	1220	1.7	71030	100.0
	5.3		11.7		19.5		6.1		2.2		10.1	
1945-1964	24600	17.4	57310	40.5	35840	25.4	12610	8.9	11000	7.8	141360	100.0
	15.4		25.4		25.4		10.3		19.6		20.1	
1965-1980	48960	28.9	67570	39.9	21630	12.8	17040	10.1	14050	8.3	169250	100.0
	30.6		30.0		15.3		13.9		25.1		24.0	
Post 1980	53670	25.6	31480	15.0	48360	23.1	54410	26.0	21630	10.3	209550	100.0
	33.6		14.0		34.2		44.5		38.6		29.7	
Total	159930	22.7	225380	32.0	141240	20.0	122410	17.4	56040	7.9	705000	100.0
	100.0		100.0		100.0		100.0		100.0		100.0	

It is assumed that MWTs will not cause disturbance to their owners (as they have the ability to remove them) and therefore it is not necessary that the prediction scheme to be developed within the project should apply to detached dwellings. As seen in Table 2 this represents around 18% of the housing stock. However, due to the limited number of installations it may be advisable or necessary to include some such dwellings in the trials so that experimental data on noise and vibration transmission can contribute to the development and testing of the prediction scheme.

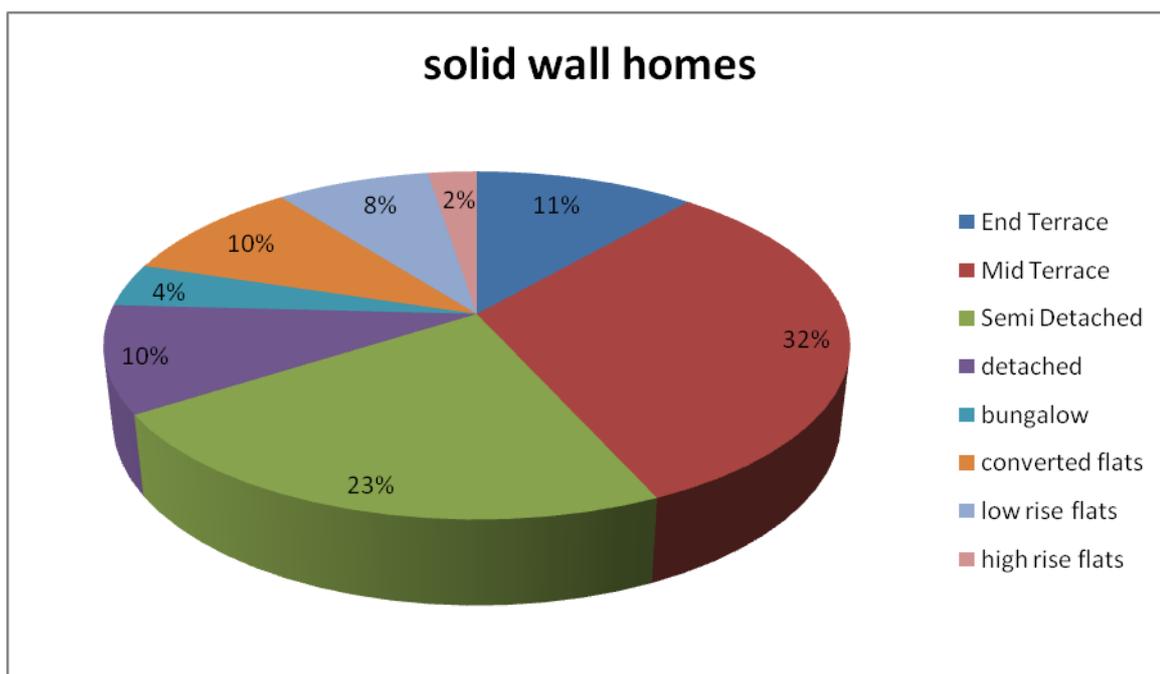


Figure 1: Break down of solid wall homes according to type (English Homes Condition Survey)

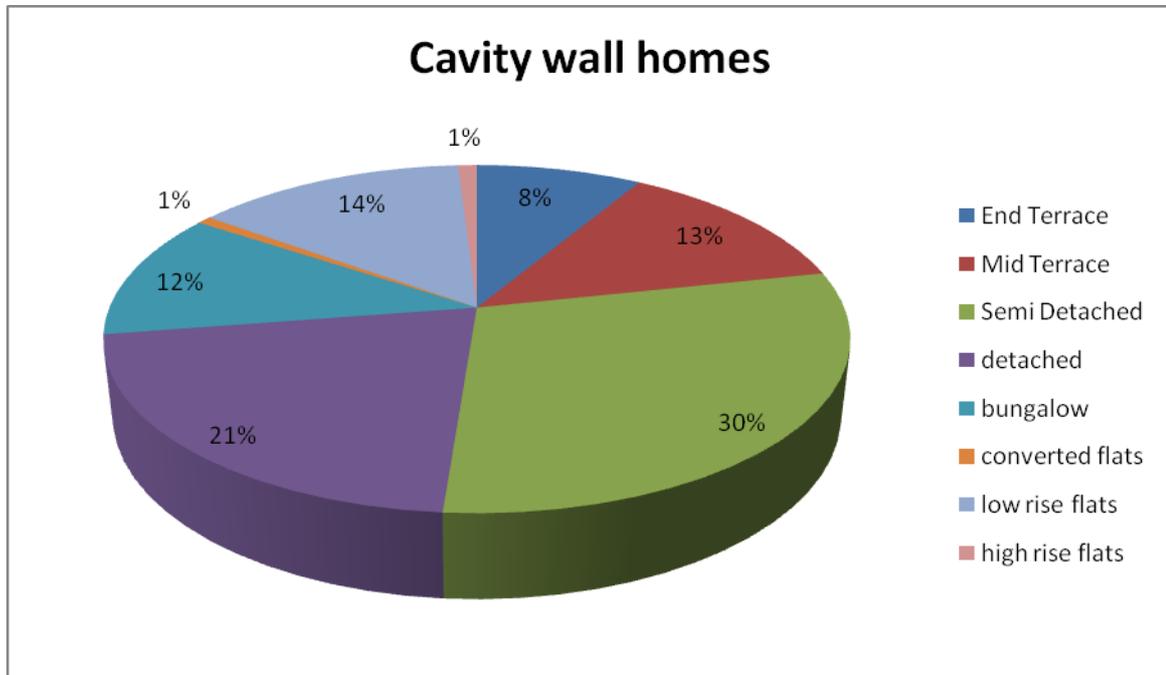


Figure 2: Break down of cavity wall homes according to type (English Homes Condition Survey)

The data in Figure 1 and Figure 2 show an increasing trend in the post war years to build detached and semi detached homes. This can be seen in the increasing proportion of this type of home with cavity wall insulation. We have used data in the EHCS detailing the applicability of insulation measures to the housing stock to infer this data on building types.

The majority of homes are masonry, with terrace, end terrace, semi-detached houses and bungalows forming 84% of the stock. It is not known what proportion of masonry dwellings are stone as opposed to brick. In 2007, 2% of solid wall and 1% of cavity wall dwellings were high rise flats where there is the possibility of roof mounted installations. No data is available but it is assumed that these roofs will predominantly be of concrete construction. Thus, it seems that solid and cavity brick walls, together with concrete roofs, as identified previously will cover the majority of potential installation sites.

The question arises as to whether any other construction types may become important in the future. Steel and timber frame constructions seem likely to become more

common in the future, together with techniques like SIPs (structural insulated panels, usually consisting of a lightweight sandwich construction with thermal insulation as the core). No official sources of information are available from which it is possible to estimate the potential importance of such construction types for MWT installations. However, the lighter construction types, such as timber frame and SIPs will require careful analysis to determine how a turbine could be safely attached to the building. Retrofitting turbines to such buildings would be difficult as the mounting systems would need to be designed into the building at construction. Thus, we would expect a customised mounting system for such constructions.

2.9 Acoustic and vibration properties of common construction types

From the above discussion, solid and cavity masonry have been identified as the most common construction types. Steel and timber frame have also been mentioned as construction types that may form a more significant proportion of the housing stock in the future. In this section the vibro-acoustic properties, which will affect the propagation of structure-borne sound and vibration throughout the building, will be considered for the different construction types.

The most important properties of the building in terms of structure-borne sound transmission are:

- (a) the ‘mobility’ of the mounting points;
- (b) the vibro-acoustic transfer functions¹ from the point of attachment to the receiver location,
- (c) the transfer mobility of the structure between the mounting point and receiver location.

The contact point mobility (a) determines how much vibrational power is injected into the structure by the attached vibration source (MWT). The vibro acoustic transfer function (b) determines how vibration is transmitted through the building structure as vibration and then radiated as sound. The transfer mobility (c) determines the extent to which vibration is transmitted.

The transmission properties, (b) and (c), have not been studied anything like as widely as the airborne and impact sound insulation properties of buildings. However, various aspects of the transmission has received some attention, for example Cremer et al

¹ Strictly speaking these should be called ‘frequency response functions’ rather than ‘transfer functions’ but the latter is widely used in this context.

(Cremer et al. 1975) laid down some basic theory for transmission through junctions of walls. Vibration transmission through buildings has also been widely studied in the context of Statistical Energy Analysis (SEA) (Craik 1998, Hopkins 2003). Whilst it is fair to say that there is a reasonable understanding of the phenomena involved, the problem is a complex one and to date there is no universally accepted approach for prediction of vibration transmission through buildings. Arguably, the simplest general approach is the method for prediction of flanking sound transmission through building structures outlined in EN12354 (discussed in more detail in Section 4). However, except in simple cases, the EN12354 method still relies on measured sound insulation data for the walls and floors involved in the transmission and until recently was not adapted to the problem of excitation by a structure-borne sound source.

The first of the building properties mentioned above, the mobility (a), is easier to summarise. Masonry structures behave in a similar manner to large plates, whose behaviour is well known. Their mobility tends to lie within relatively narrow bounds between around 10^{-5} and 10^{-6} m/s/N (Craik 1998, Cremer et al. 1975, Hopkins 2007). Figure 3 shows mobilities calculated for a range of masonry constructions. Although in real buildings there will be some variation of the mobility about the straight line due to resonances, these values provide a good estimate of what might be expected in practical structures. The mobility of steel frame structures is however expected to show considerably more variation. Shown in Figure 4 are the mobilities of some structural steel I beam sections varying in width from 100mm to 150mm. In practice a considerably wider range of values is likely to occur: first, a wider range of sizes is expected, secondly the mobility of an I beam depends on whether it is excited parallel or perpendicular to the flange and thirdly a large variation is expected depending on local detail, specifically, whether the excitation is on or off the neutral axis.

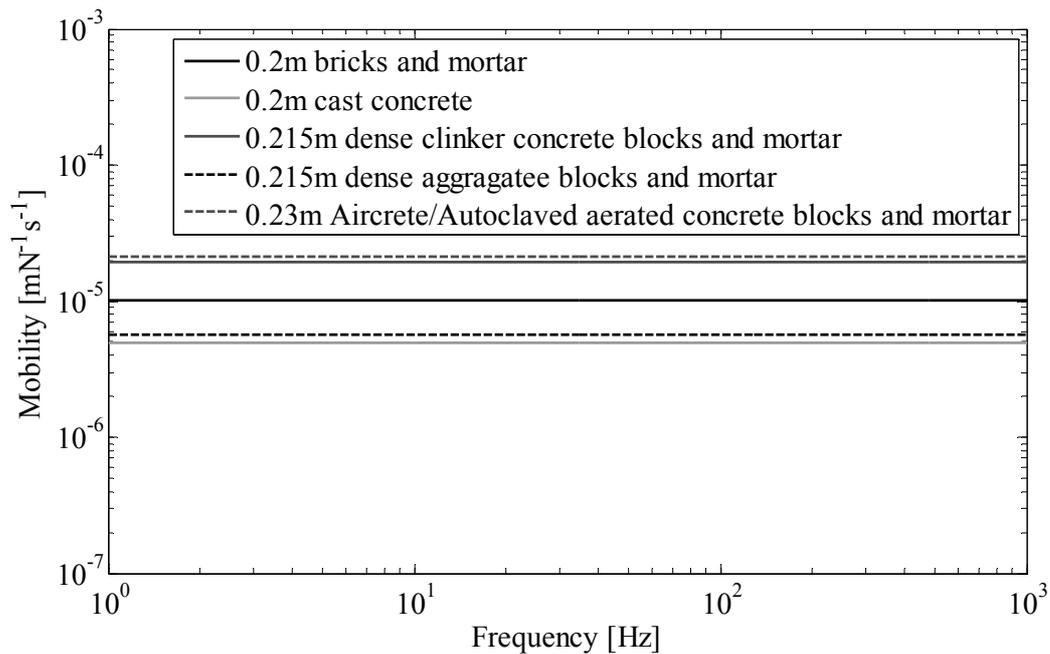


Figure 3: Mobilities of large masonry plates

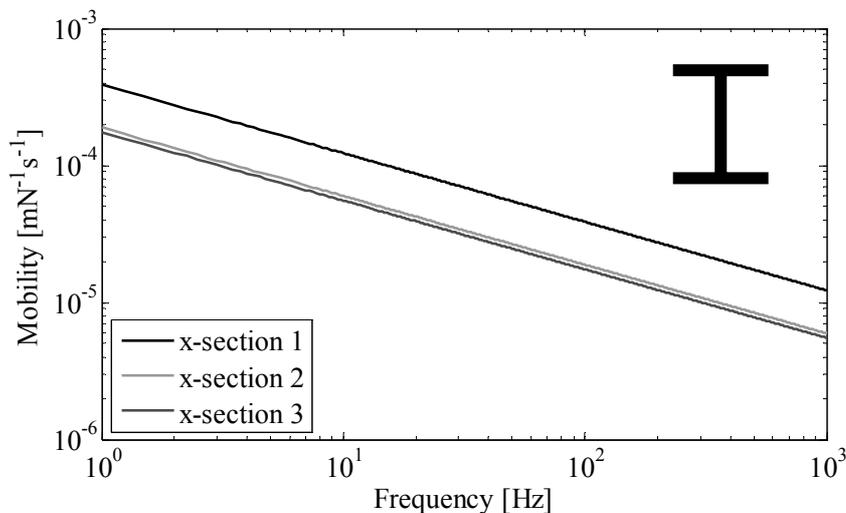


Figure 4: Typical mobilities of structural I beams

It has been mentioned above that timber frame and SIPs constructions will require local reinforcement in order to support a MWT. Such reinforcement will generally be expected to have a significant effect on the mobility of the structure at the connection points. Therefore, the transmission of structure-borne sound power into the building structure will depend strongly on local details. Whilst this could be beneficial in that it opens up the possibility of designing the reinforcement to minimise sound transmission it raises significant difficulties in terms of prediction since the full details

of the attachment must be available first. In practice, we would expect prediction of the mobility not to be straightforward even if the full details were available.

From the above we conclude that it is possible to make fairly general statements about the properties of masonry structures and their mobility can be predicted with good confidence from density and thickness. On the other hand, the performance of other structural types, timber frame, steel frame and SIPS is expected to depend strongly on the local detail which will be different for every installation. Prediction of the input mobility, and therefore the structure-borne sound power transmission, is not expected to be easy even if the full details of the attachments are available.

2.10 Conclusions

From the above we conclude that there is a small range of MWT models available, effectively three turbine types, two of which may be wall or roof-mounted and one which may only be wall mounted. However, the range of installations is wider because of the different building types involved. Cavity and solid brick constructions and flat roofs were the most common in the Warwick Wind Trials and also account for the majority of dwellings within existing housing stock.

The acoustic and vibration properties of masonry constructions can to some extent be generalised. However, the same cannot be said for steel and timber frame and modern constructions like SIPs, whose properties are expected to vary widely depending on the details of the points at which the MWT are attached. The need for local reinforcement at these points will make it difficult to include such constructions in a simple prediction method. This, together with the fact that masonry constructions are the most common in the UK, provides an argument to focus the prediction method towards masonry constructions. Nevertheless, the methodology should be developed so as to allow other constructions to be included whenever sufficiently detailed information is available (this point is discussed further in Section 4.3).

The Ashenden House study concluded that urban wind turbines do not acoustically affect the residents or the urban environment. However, we have argued that this conclusion may not apply generally to MWTs. Complaints were made about noise from roof-top installations in the Warwick Wind Trial and the installation was judged by EHOs to be causing a statutory nuisance. This experience has significant implications for permitted development rights and justifies the research within the project.

3 Characterisation of structure-borne sound sources

3.1 Introduction

The main question to be considered in this Chapter is how to ‘characterise’ MWTs as sources of structure-borne sound, in other words, how to describe the ability of the MWT to excite structure-borne sound and vibration in connected buildings structures. Throughout this chapter the terms ‘structure-borne sound source’ and ‘vibration source’ are taken as equivalent.

Standard methods for characterisation of airborne (acoustic) sound sources have been available for many years, and the resulting data is widely used, for example in certification schemes like CE marking. However, the state of the art for structure-borne sound sources lags far behind. One of the main difficulties is that whereas the source strength for an airborne sound source is taken to be a constant, structure-borne sound sources may be attached to a range of different ‘receiver’ structures, for example different building constructions, and in every case the excitation is different. There are other difficulties too which will become evident.

3.2 Background theory

The basic equations describing the behaviour of a vibration source and a vibration receiver when coupled and uncoupled are outlined in appendix A, see also (Cremer et al. 1975). Here however, the analogy of an electric circuit (being equivalent to a coupled vibration source and receiver) will be used to illustrate the problem in a more familiar way. This approach is often used to solve or illustrate vibration problems (Gardonio and Brennan 2002). When using this analogy one relates the source of vibration to an electrical power supply as shown boxed in Figure 5.

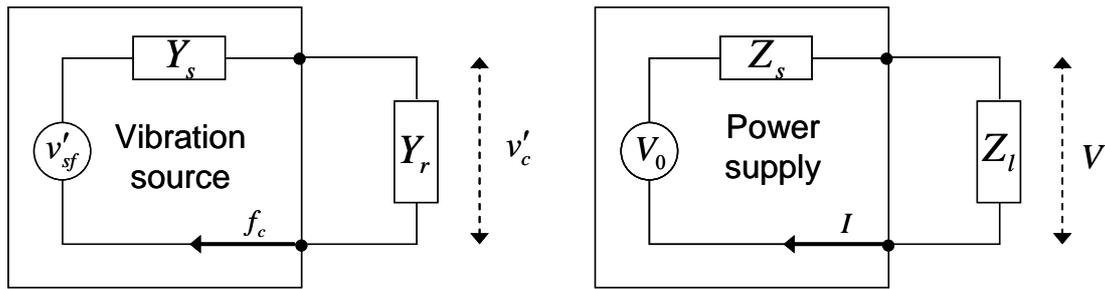


Figure 5: Vibration source analogous to a power supply. Left - circuit diagram representing an installed vibration source where the load is the mobility of the support structure Y_r . Right – an electrical power supply connected to an impedance Z_l . The force f_c applied by the source to the receiver is analogous to the current I in the equivalent circuit

Figure 5 shows an active vibration source coupled to a receiver structure of mobility Y_r (left) and a power supply connected to a load impedance Z_l (right). The current in the electric circuit, I , and the voltage across the load, V , is dependent on the load impedance Z_l , the power supply’s internal impedance Z_s and the open circuit voltage V_0 of the power supply. Analogous to this is the vibration case where the contact force and velocity, f_c and v_c respectively, correspond to the electrical circuit current and the voltage across the load impedance. Equations (1a) and (1b) below illustrate this most clearly.

$$Z_l = \frac{V}{I} \qquad Y_r = \frac{v'_c}{f'_c} \qquad (1a,1b)$$

The essential point from the above is that the forces applied to the building depend on both the source (the MWT) and the receiver structure (the building).

Figure 6 illustrates the source receiver system in terms of a wind turbine (source) and building/mount combined (receiver). The mobilities Y_s and Y_r are the mobilities at the points where the source and receiver structures couple. Thus the operational velocity v'_c of the wind turbine can be related to the force at the connection point f'_c using the mobility of the receiver structure.

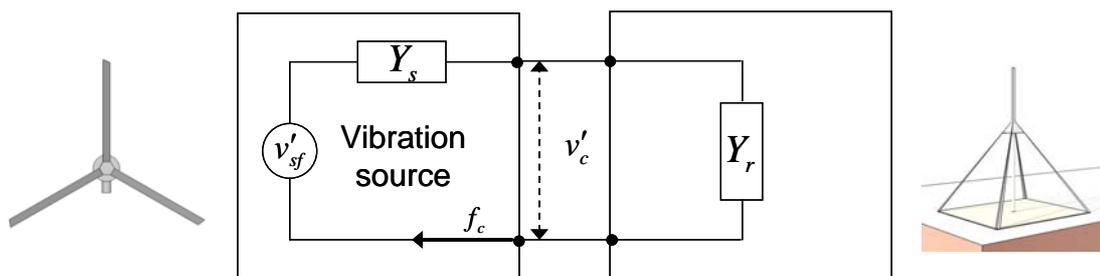


Figure 6: Representation of a wind turbine and mount system using an electrical circuit analogy.

In terms of structure borne sound it is these operational contact forces with which we are most concerned since this force input excites the receiver structure causing it to vibrate and hence to radiate sound. The velocity is also of interest because the product of the force and velocity gives the transmitted vibrational power. Power will be addressed in a later section. First however we consider how one might determine the force at the interface between source and receiver.

3.3 Force identification

It can be seen from equation (A.7) of appendix A that the structure borne noise or vibration at a point of interest can be determined from the force applied to a receiver structure by an operational vibration source. In order to do this a measurement of the frequency response function H_r of the uncoupled receiver is required but usually the main difficulty is quantifying the force on the receiver f'_c . A great deal of research has been dedicated to this problem and two distinct measurement approaches have been developed:

- Direct force measurements using a force sensor between the source and receiver
- Inverse methods which determine the force indirectly from more easily measured quantities.

In terms of the electrical circuit analogy the direct measurement of forces is equivalent to the measurement of current. Inverse methods therefore use a measure of the velocity (voltage) and mobility (load impedance) to determine the force (current) indirectly.

3.3.1 Direct measurement methods

Assuming a single contact interface, the direct measurement of contact forces would be achieved by inserting a calibrated force sensor between the source and receiver structures at the connection point. It would then be possible to measure the force on the receiver whilst the source is operational and this force could then be used as an input to equation (A.7) to predict a sound pressure or velocity. For simple cases where a source is coupled to a receiver at a single point which is restricted to motion in a single direction the approach is sensible and is known to work, see (Lai 2007) for example. However, with the lack of standardisation in this area the extent to which the method is applicable is not clear. Also there may be concerns that the force transducer in the connection alters in some way the force on the receiver. Nevertheless, work is currently progressing towards the standardisation of this

approach and a draft standard has already been produced which describes the measurement of forces in bolted connections, ISO/WD 18312-1. In practice however the direct force measurement approach is not as straightforward as it first seems, especially for complex cases.

Up to this point a single point connection with the freedom to move in one degree of freedom only has been used to describe the direct force identification approach. In practice relatively few simple cases of this type are encountered. More often, problems involve multiple connection points with up to six degrees of freedom: translation in three orthogonal directions and rotations about these orthogonal axes. It is in dealing with complex problems of this type that the shortcomings of this approach are most apparent. In fact this is one of the main difficulties in structure borne source characterisation in the general sense and is unfortunately largely unavoidable. Some methods however are better suited to dealing with this difficulty than others. To illustrate this issue we shall use the example of a wind turbine.

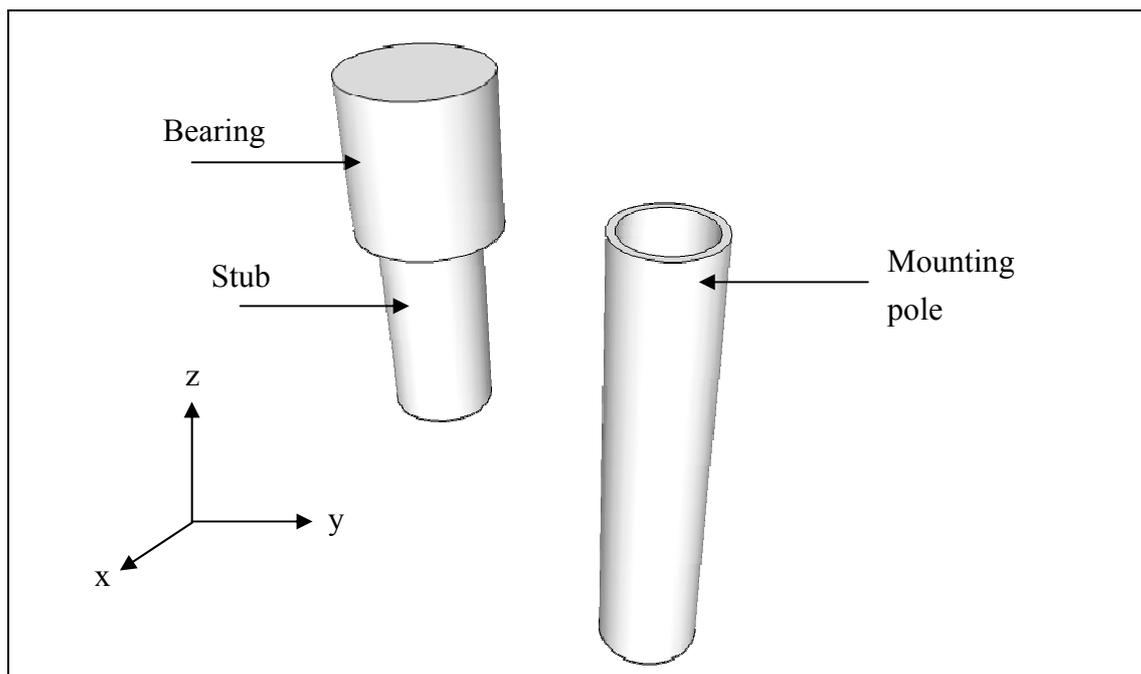


Figure 7: Wind turbine coupling point (left) and wind turbine mounting point (right). The wind turbine and mounting are coupled by inserting the stub into the pole. Shown at the bottom left of the figure are orientation axes, z is the vertical direction parallel to the edge of the system and the x and y axes are perpendicular to the pole and mount.

Shown in Figure 7 is an illustration of the coupling points for a typical wind turbine (source) and mounting system (receiver). For the source, only the stub and bearing are shown, and for the receiver, only a short length of the mounting pole is included in the figure.

Referring to Figure 7 it is clear that without modification of the source and/or receiver structure it will not be possible to incorporate even extremely small force transducers (with cables) into the connection between source and receiver. Furthermore it is difficult to imagine how forces in the vertical z-direction would be measured at all, not to mention the possible requirement to measure moments about the x and y axes. Modification of the source or receiver connection points in this case would not be an option since this would reduce confidence in the measured forces. To further illustrate this, shown in Figure 8 is a photograph of a typical wind turbine mounting point.



Figure 8: Photograph of Turbine 1 connection point. The stub is designed to be inserted into a mounting pole

Overall it is clear that for a complex system such as a wind turbine which has the freedom to move in multiple degrees of freedom it is not a simple matter to obtain contact forces using direct measurements, mainly because it is not straightforward to integrate the required transducers into the connection. Thus, for the many instances where direct force measurements are not possible, industry tends to favour an alternative approach; often referred to as “inverse force synthesis”.

3.3.2 Inverse methods

Inverse force synthesis, also known as inverse force identification, is a method for the determination of contact forces indirectly from measurements of related quantities (Blau 1999, Dobson and Rider 1990). The method has been well proven and has become highly developed; mainly because of its use in the automotive industry (Vandenbroeck and Hendricx 1994). For the single connection point case, the inverse

force synthesis approach obtains the receiver force, using equation (1b) or similar, perhaps in terms of acceleration or displacement. The force from equation (1b) can then be used as the input into equation (A.7) which in turn would yield, for example, a structure borne sound pressure or a vibration velocity at a point of interest. When used in this way, the combination of equations (1b) and (A.7) provide an approach, often referred to as transfer path analysis (Van der Linden and Fun 1994). To perform a transfer path analysis the frequency response functions describing the receiver Y_r and H_r would be measured whilst the source and receiver were separate and the coupled velocity v'_c would be measured whilst the source operates in-situ.

The main advantages of inverse force synthesis over direct force measurements are that velocity measurements can be made externally to the connection which means that no modification of the connection should be required. As a result the measurements are easier to perform and there may be greater confidence in the reliability of the forces obtained. A further advantage is that the method can deal more easily with multiple connections and multiple degrees of freedom.

In order to allow for multiple points and degrees of freedom the problem must be reformulated using simultaneous linear equations which can be most easily presented in matrix form (O'Hara 1966). For example equation (1b) becomes,

$$\mathbf{v}'_c = \mathbf{Y}_r \mathbf{f}'_c \quad (2)$$

where matrices are denoted by uppercase bold and vectors lower case bold. Thus \mathbf{v}'_c is an n -dimensional column vector of n velocities, \mathbf{Y}_r is an $n \times m$ matrix of receiver mobilities and \mathbf{f}'_c is an m -dimensional vector consisting of m operational contact forces. Inverse force synthesis in the multi-point, multi-degree of freedom sense therefore requires several mobility and velocity measurements to provide the inputs for equation (2) which must then be solved, possibly numerically, to find the vector of operational forces. In order for a solution to be obtained the number of response measurements n must be at least equal to the number of forces to be determined m , and typically n is chosen to be greater than m by a factor of two or more (Mas et al. 1994, Otte 1994). As such, often the required measurements and the subsequent data analysis are challenging.

Overall, the inverse force identification approach is not always simple to apply in practice but the invested effort is usually balanced by the quality of the predictions obtained. The approach could potentially be used to determine the forces applied by

an operational wind turbine to a mount system or by the mount system to a building. There are however a number of limitations of the approach which would make this somewhat impractical in the broadest sense.

3.3.3 General comments on contact force identification

Two methods which allow for the determination of operational forces, directly and indirectly, have been briefly described. An alternative method which applies only to resiliently mounted vibration sources (Vandenbroeck and Hendricx 1994) was not included however as it was seen to be of little relevance to the characterisation of micro-wind turbines which in most cases are rigidly mounted to a pole. It was concluded that the direct measurement of forces would not be appropriate for most micro turbines as it would not be possible to integrate the required sensors into a realistic installation. On the other hand, the inverse approach to force identification could potentially be applied to the problem. There does however remain a question of whether the operational contact force is an appropriate way to characterise a structure borne noise source as there are arguments to suggest otherwise.

Shown in Figure 9 is a result from a recent study (Moorhouse et al. 2009). The figure shows the contact force at one point between a vibration source and receiver measured using inverse force synthesis in the laboratory. The result clearly shows that the contact forces, even when measured on two very similar receivers, can be quite different. In this case, idealised laboratory structures were used for the source and receiver, but the results are representative of real machines. For this reason many researchers advocate the use of independent quantities to characterise the source irrespective of how it is installed. Independent descriptors are reviewed in the next section.

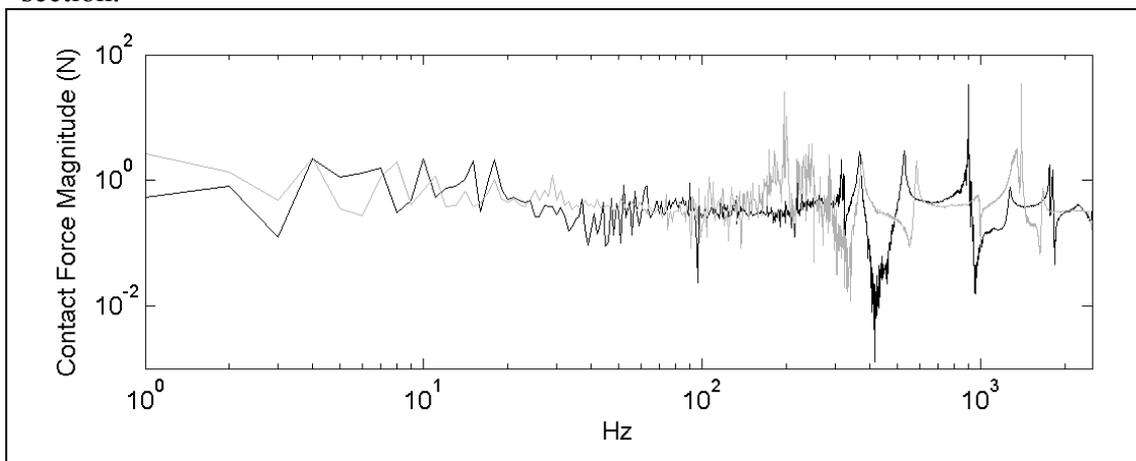


Figure 9: Contact forces measured using inverse force synthesis for one source on two different receiver structures

3.4 Independent source characterisation

Obtaining the contact forces as described above is an accepted method used extensively by industry. Although useful the approach is not ideal for applications where the receiver structure may vary, as in this project. This is because, as described above, the same source can generate different forces when attached to different receiver structures. It is therefore not possible to use such data to predict how the source will behave when connected to a different receiver structure. This is a major limitation of contact force data because a source must be repeatedly characterised for every receiver structure of interest or even if only slight modifications are made to an existing receiver. One alternative, independent source characterisation, is so called because the data obtained is a property of the source only, i.e. it is independent of any receiver structure. Independent source characterisation data can in theory be used to predict the behaviour of any source when coupled to any receiver and as such is generally considered as the ideal (Ten Wolde and Gadefelt 1987).

To independently characterise a vibration source a description of its active and passive properties are required (Petersson and Gibbs 2000):

- passive properties: mobility or impedance
- active properties: free velocity or blocked force.

The free velocity and blocked force can also be combined to provide a single power-based descriptor called the characteristic power (Moorhouse 2001) which will be discussed later.

A standard procedure exists for the measurement of mobility ISO 7626-2 and ISO 7626-5, from which the impedance can also be obtained (O'Hara 1966). The ISO9611 standard effectively describes how the free velocity may be measured. A further standard, similar to ISO9611, also exists but for the specific application of internal combustion engines in BS ISO 13332:2000. No measurement standard exists for the blocked force but work towards standardisation of the direct measurement of structure borne power transmission ISO/WD 18312-1 which involves direct force measurements will likely be applicable to some extent.

3.4.1 The free velocity

Returning to the analogy between a vibration source and electrical power supply, shown in Figure 10 is an ac power source (right) compared to an equivalent circuit for a freely suspended vibration source.

Without an electrical load on a power supply no current, I , flows and the internal impedance therefore has no influence on the measured voltage, V . The voltage measured across the unloaded power supply is in a sense analogous to the vibration velocity of a vibration source when there is no external load; this corresponds to a free structure with no external forces, f , acting (force analogous to current). We may therefore define the free velocity, v'_{sf} , as the vibration velocity of the source when there is no force applied by a connecting structure, see appendix A.

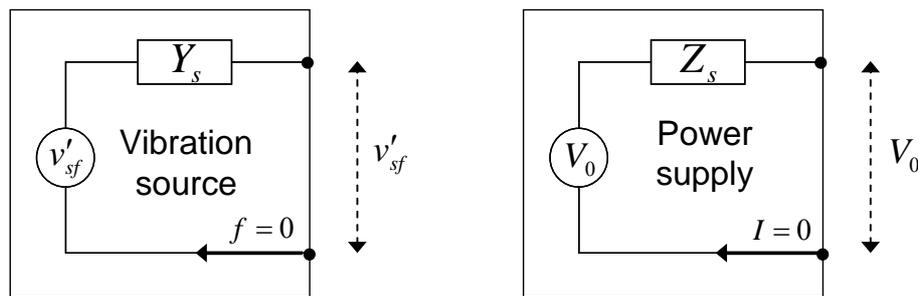


Figure 10: Open circuit analogy. Left - circuit diagram representing an freely suspended vibration source with no operational load. Right – an electrical power supply with no load. The velocity of the vibration source under no load is analogous to the voltage across the power supply when no current flows which would be the case when there is no electrical load.

The free velocity of a source is therefore the velocity measured on the contact points when the source is not connected to any receiver structure but is ‘freely suspended’ and operational. In practice this means that the source must be mounted on very soft springs. It has the major advantage that it characterises the source independently of the receiver structure. Also, a measurement standard exists, which remains one of the only standardised approaches in this field. However, a major practical difficulty is in achieving the free boundary condition because very few vibration sources are designed to operate under these conditions. Clearly, it would be impossible to achieve these conditions for a MWT under representative operating conditions.

A possible alternative which is not sensitive to wind loading is the measurement of blocked force.

3.4.2 The blocked force

If we now consider a short circuit (Figure 11), in this case no voltage is measurable across the power supply and the current is the maximum deliverable. This corresponds to a vibration source whose motion is restricted so that the velocity, v'_s , at its contact point is zero, known as a blocked condition. The force required to

achieve this is referred to as the blocked force f_{bl} . To measure the blocked force it is not possible to use conventional inverse force synthesis because the velocity of the coupled source and receiver must be zero to achieve the blocked condition. This leaves only the direct measurement of blocked forces as an option where the source is attached to a massive, heavy structure. This is not appealing for the same reasons as outlined previously but also because achieving the blocked condition in practice is not straightforward.

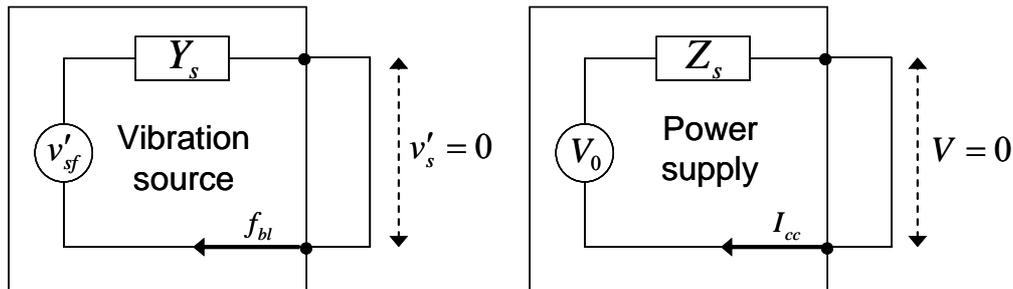


Figure 11: Short circuit analogy. Left - circuit diagram representing a blocked vibration source. Right – an electrical power supply short circuited. The force required to block the source is analogous to the current in the short circuit.

The main argument for measuring blocked forces as opposed to free velocities is the possibility to run the vibration source under a realistic load during characterisation measurements which would be required for a MWT. This, although a significant advantage, has not proven sufficient for the method to be taken up by many researchers or practicing engineers however. In fact very few case studies exist and blocked force measurements tend only to be made when there is no other option available. One exception to this is an automotive paper describing the measurement of blocked forces for a vehicle suspension system (Gaudin and Gagliardini 2007) which is a relatively complex problem. Reasonable predictions of vehicle interior structure borne noise were made using these blocked forces. The approach used was to load the suspension system with a heavy concrete blocking mass and to measure the forces between the blocking mass and the suspension system under rolling road excitation. Another approach for measuring blocked forces is described in (Ten Wolde et al. 1975) which uses the measured velocities of a known blocking mass attached to the source. This method however would not allow for a source to be operated under load and as such has no real advantage over the measurement of free velocity. Unfortunately, neither of these methods could easily be applied to the case of a MWT without significant difficulty or compromise.

3.4.3 General comments on independent source characterisation

A vibration source can be described independently by its mobility and free velocity or blocked force. This principle is widely accepted although there are significant practical problems to overcome in order to obtain either the blocked force or the free velocity. It is also the case that predictions made using such characterisation data often show poor accuracy and the cause for this is not well understood.

Overall the conventional methods described for the measurement of free velocity or blocked forces are not suitable for the characterisation of a micro wind turbine.

3.5 In-situ source characterisation

Methods which allow for source characterisation data to be obtained whilst a source is installed can be described as in-situ characterisation methods. The inverse force synthesis approach described earlier is partly performed in-situ but the source and receiver have to be separated to measure the receiver mobility at some stage. The methods described in this section allow one to characterise the activity of structure borne noise sources without dismantling the assembly, i.e. without separating the source and receiver structures. From a practical point of view this is a major advantage because the source in its natural environment can be operated properly under load and time is saved because the assembly doesn't have to be taken apart. Furthermore no special test rigs should be required as would be the case for conventional free velocity or blocked force measurements. The methods described here relate to the measurement of active source properties rather than passive.

3.5.1 Characterisation methods for resiliently mounted machines

An in-situ method for source characterisation and the prediction of structure borne power transmission was investigated by Moorhouse and Gibbs in (Moorhouse and Gibbs 1995, Moorhouse and Gibbs 1993). It was shown that for resiliently mounted machines both the free velocity of the source and the mobility of the receiver could be measured in-situ allowing for power transmission from source to receiver to be quantified. Predictions of structure borne power transmission obtained using the free velocity and receiver mobility were found to compare well with powers predicted using a cross spectral method (Pinnington and White 1981).

The main drawback of both these methods with respect to building mounted wind turbines is that they can only be applied to resiliently mounted vibration sources. Typically a wind turbine is rigidly mounted to a pole preventing source

characterisation at this interface using these approaches. A further downside is that the requirement to know the properties of a resilient mount could potentially lead to uncertainty. Overall, the difficulties associated with these approaches will in practice be no easier to get around than the difficulties associated with the measurement of free velocities for MWTs. The advantage of such approaches is that resiliently mounted machines can be characterised in-situ.

3.5.2 Pseudo-forces

For the more general case where the source mount type need not be resilient, two methods for characterising structure borne sound sources in-situ were described in (Janssens et al. 1999, Janssens and Verheij 2000, Janssens et al. 2002). In (Janssens et al. 1999) a method for obtaining an set of source excitation forces is explored using an inverse approach, and in (Janssens and Verheij 2000, Janssens et al. 2002) a similar approach is proposed for measuring similar sets of forces which are referred to as pseudo forces. As the two methods are very similar, here we shall discuss the more recent-pseudo forces approach validated in (Janssens et al. 2002).

The so called pseudo-force can be obtained by measuring the frequency response functions of the assembly by exciting any point on the source whilst measuring the acceleration response at any point on the assembly, and then while the source is operational the response point acceleration is monitored. It is then considered that the force given by the product of the inverted frequency response function and the operational acceleration may be considered as the force required to reproduce the activity of the source by external excitation. Although this is an approximation, by extending the method so as to use multiple force and response positions, it is argued that the approach becomes more valid and this is confirmed experimentally.

The motivation behind this approach is firstly to avoid the requirement to dismantle the coupled source and receiver structures as would be required for inverse force synthesis. Furthermore it is argued that, by nature, the pseudo forces are an independent property of the source as they are the forces required to reproduce source behaviour. This concept is therefore of interest for the characterisation of MWTs as it is one of very few approaches which could potentially be used.

The only downside of this approach is that there is no evidence to support how these pseudo forces can be used to predict the behaviour of a source when attached to a receiver structure other than the one on which it was characterised. This approach is therefore not ideal for this project.

3.5.3 In-situ blocked force

The direct measurement of blocked forces was described in 3.4.2 in which the advantages of blocked forces as an independent characterisation were also described. Despite these significant advantages there has not been extensive use of the approach due to difficulties relating to the required measurement procedure. It has recently been shown however that the blocked force of a vibration source can be obtained by measurements made in-situ on an installed source (Moorhouse et al. 2009).

The required relationship can be derived from the conventional theory outlined in appendix A without the need for additional assumptions. The form shown here, equation (3), relates to measurements made at the contact points of the coupled source and receiver but a more general result allowing for remote measurement positions to be used is also possible.

$$\mathbf{f}'_{bl} = \mathbf{Y}_c^{-1} \mathbf{v}'_c \quad (3)$$

The blocked force can be obtained from measurements performed entirely in-situ using equation (3). Two measurements sets are required; one of the mobility matrix for the coupled structures \mathbf{Y}_c and one of the operational coupled velocity \mathbf{v}'_c . The approach is very similar to that used in inverse force synthesis but with two distinct advantages: firstly the blocked force is an independent property of the source and secondly the source and receiver do not have to be separated to perform the characterisation measurements. The independence of the blocked forces is illustrated in Figure 12 where it can be seen that the blocked force measured on two different receiver structures (top) are largely the same whereas contact forces measured by inverse force synthesis (bottom) for the same two receiver structures are quite different. The results shown in Figure 12 are from the same study as those shown in Figure 9 (Moorhouse et al. 2009). The only difference is that here the results are shown in one third octave bands as is usual in building acoustics.

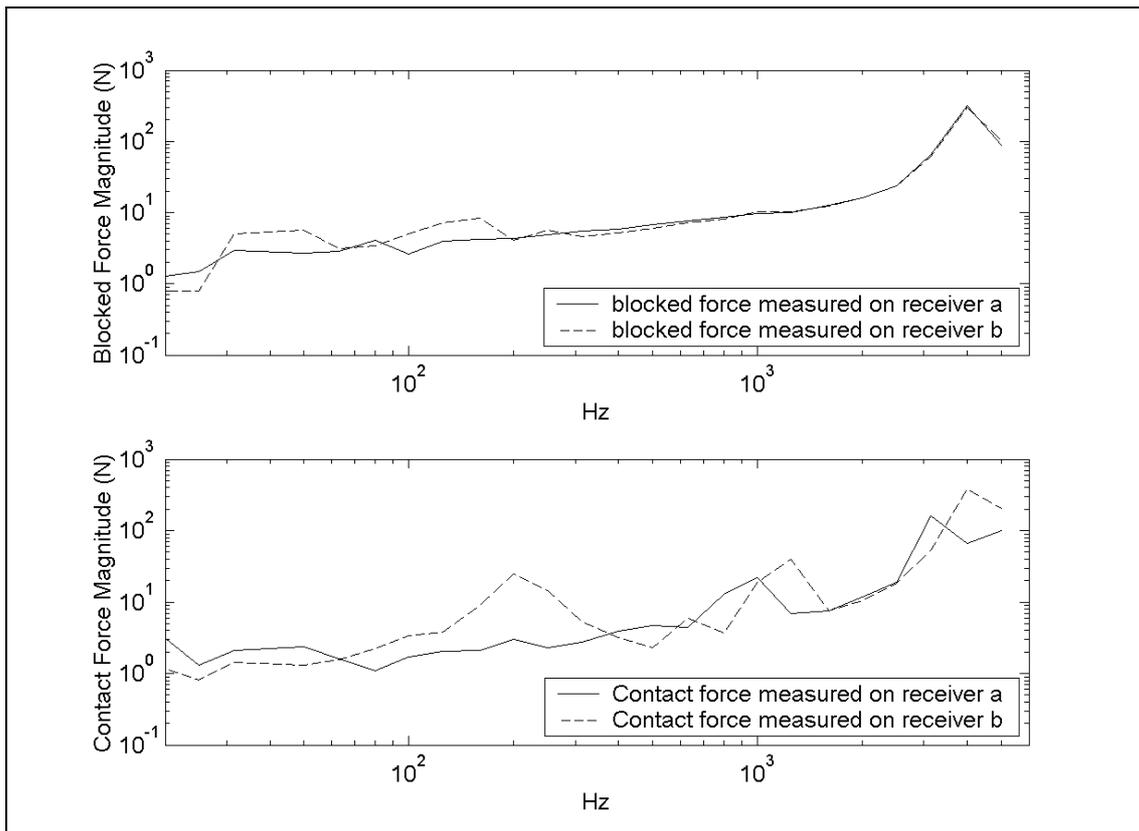


Figure 12: Blocked forces (top) and contact forces (bottom) for one of two contact points of an ideal source measured on two different receiver structures

A further advantage of this approach is that a simple relationship describing the coupled structures can be used to predict structure borne sound or vibration at a point of interest. This differs from the approach used in transfer path analysis because the quantity relating force to response is a property of the assembly rather than the receiver structure in isolation. This approach was used in (Gaudin and Gagliardini 2007) to predict the structure borne noise in a vehicle interior from blocked forces which were measured directly.

3.6 Power

Sources of airborne sound are generally rated in terms of their sound power emission. Describing structure borne sound sources in terms of the power transmitted from a vibration source to its receiver structure is also possible. Described in this section are two possible quantities which could potentially be used to characterise a vibration source: the structure borne sound power and the characteristic power.

3.6.1 Structure borne sound power

The power which is transferred from an operational vibration source to a receiver structure is known as the active power or structure borne sound power. The active

power can potentially be measured by monitoring the velocities and forces at the contacts between the source and receiver and taking the real part of their product. Alternatively power could be measured in a laboratory, for example using a reception plate (Späh and Gibbs 2009). The active power could therefore be considered as a quantity to be used for structure borne source characterisation. This initially appears sensible as airborne sound sources are usually characterised in terms of their sound power.

Unfortunately the structure borne sound power does not lend itself well to this purpose however as it is not an independent property of the source. This means that comparing two structure borne sound powers measured on different receiver structures would be in most cases meaningless. The structure borne sound power, as a characterisation quantity, therefore has the same limitations as the contact forces.

3.6.2 The characteristic power

The problem with using structure borne power to characterise vibration source activity is well known and as such, attempts have been made to address the issue. One proposal was the source descriptor and coupling function outlined in (Mondot and Petersson 1987). The approach basically breaks down equation (A.8) into two components, one which includes only source properties (the source descriptor) and one that includes both structures and describes the potential for power transmission (the coupling function). The main value of the approach is in the simplified representation of the problem which is conceptually more useful than equation (A.8) in its usual form. There is no real simplification in terms of measurements however because the required data is the same as that which would be required for independent source characterisation anyway. A further limitation of the source descriptor and coupling function is that they were defined only for the single point case.

In order to address the limitation of the source descriptor described above, three alternative characterisation quantities: the maximum available power, the mirror power and the characteristic power were proposed in (Moorhouse 2001). All three were defined for the realistic case where there are multiple connections between the source and receiver structures. The characteristic power can be defined in a number of ways but most simply it is the product of the free velocity and the blocked force.

It is shown that the characteristic power may be useful as an estimate of the upper bound for power transmission for a given source. This therefore means that the characteristic power could potentially be used to compare one vibration source to

another since the source with the lower characteristic power is likely to result in less structure borne sound. Another advantage is that the characteristic power is a single frequency dependent value and so can be easily compared to other characteristic powers. This is an advantage of the characteristic power over free velocities for example, for which there would be $N \times D$ sets of frequency dependent data where N is the number of connection points and D the number of degrees of freedom. The characteristic power is therefore a neat way of combining all of the source characterisation data into a single figure which gives a good indication of the power likely to be transmitted by a vibration source. The only downside is that obtaining the characteristic power may not be straightforward as typically the full independent source characterisation procedure would be required. As such the characteristic power does not provide a simple way to take measurements but rather a simple way to present the source characterisation data.

The recent measurement standard EN 12354-5:2009 proposes the use of the characteristic power for the estimation of structure borne sound from service equipment in buildings. The standard also concedes that suitable measurement procedures to obtain the characteristic power are not yet widely available. However, some approximate methods are described for specific source types like water supply components in annex D of the standard.

3.7 Source characterisation in relation to EN12354-5

The following chapter of the report discusses the transmission of structure borne sound with reference to the recently released building acoustics standard EN12354-5. The purpose of this section therefore is to outline the source characterisation inputs required for the prediction of structure borne sound using EN 12354-5. Other aspects of EN 12354 relating to this project are discussed in the following chapter.

In section 4.4 of EN 12354-5 the characteristic power $L_{W_s,c}$, is stated as the quantity to be used to characterise a vibration source in order to allow for an estimate to be made of the structure borne sound power transmitted to a building. A coupling term D_C for the supporting element is required to make the connection between the two. Some examples of possible ways to obtain the characteristic power are given in annex D of BS EN 12354-5. The methods described are however laboratory methods which could not be easily applied to the characterisation of a wind turbine. Moreover the methods described are simplified approaches which can be used only when certain assumptions are met.

Since the approaches described in EN 12354-5 are likely to be simplistic to obtain the characteristic power of a MWT the only alternative is to calculate the characteristic power from independent source characterisation data. Based on the arguments given previously in the chapter it is arguable that the only way to obtain an independent description of source activity for a MWT would be to measure the blocked force in-situ. Using this blocked force it is in theory possible to calculate the characteristic power providing the mobility can also be measured, in-situ or otherwise. Fortunately this is likely to be the case.

The coupling term D_c is a property of the source and receiver and so is not an independent property of the source. Details of the calculation procedures used in BS EN 12354-5 are discussed in chapter 5 of this report, including a discussion of the coupling term which shall not be repeated here. It is worth mentioning however that by choosing carefully the points used to measure the characteristic power it should be possible to determine D_c using inverse force synthesis at a number of points of interest. It is likely therefore that after some preliminary investigations on a real system a robust methodology for the simultaneous measurement of characteristic power and structure borne sound power could be developed. It should also be possible therefore to define the characteristic power and structure borne sound power at the interface between wind turbine and mount and at the interface between mount and building simultaneously.

3.8 Specific characterisation issues relating to MWTs

One of the complications which has hindered progress in the area of structure borne sound source characterisation is the vast range of different problems encountered in the field, for example, limited access to the required measurement points. Some of these issues have been discussed throughout this chapter in relation to specific source characterisation approaches. In this section firstly a quick source characterisation overview will be given and then some other potential issues will be addressed, both from the point of view of MWTs.

3.8.1 Source characterisation for MWTs

In the previous sections several source characterisation approaches have been described. Relatively few of these approaches have found their way into standard procedures, the exceptions being the standards for the measurement of mobility and free velocity. In general the main difficulty in source characterisation is obtaining a good description of source activity. This was the main focus of the review.

There are essentially two issues to be considered:

- What are the best quantities to use in source characterisation, and
- How is the necessary data to be obtained for a MWT

Point two is probably the most important to address as only methods which can be applied to building mounted wind turbines can be considered. The approaches outlined were the direct and indirect measurements of contact forces, direct measurements of free velocity and blocked force and the measurement of pseudo forces and blocked forces in-situ.

In order for building mounted wind turbines to operate they must be subjected to significant wind loading which requires them to be well secured. Furthermore, realistic wind conditions would be difficult to generate in a laboratory so a field type measurement approach is required. This constraint immediately rules out the direct measurement of free velocity which is the only standard approach currently available. Similarly, the direct measurement of blocked forces can also be ruled out because building a suitable blocking structure in the field would be highly impractical. Furthermore there is little evidence to support such an approach.

A further difficulty particular to MWTs is the nature of the connection between source and receiver because the mount geometry is not easily dealt with by some of the methods described. In particular the direct measurement of contact forces poses significant problems because it would not be straightforward to incorporate the required sensors into an installation. It is also questionable whether forces can be measured accurately in this way.

Having ruled out the direct measurement of free velocity, blocked force and contact force by these feasibility arguments we now refer to the slightly lesser issue of suitable characterisation quantities.

Ideal source characterisation quantities, such as the free velocity and blocked force, give an independent source description. Other measurable quantities such as operational contact forces give a situation specific description of source activity. The drawback of a situation specific source characterisation is that the data set obtained can only be used to describe the system in which it is defined. This drawback is significant in the characterisation of MWTs because a wind turbine unit may be mounted to a range of different mast systems. If measurable, an independent

description of source activity would therefore be preferable.

Taking both arguments into account the in-situ measurement of blocked force appears to be the optimum approach for characterising a MWT. The only other approaches which are feasible are the measurement of operational contact or pseudo forces. These alternative approaches cannot currently be used to predict structure borne sound or vibration for installations other than the ones in which they are characterised and in any case do not afford any simplification of the measurements. A further advantage of the blocked force is that it can be used to calculate the characteristic power for input to EN12354-5 which cannot be said for the measurable alternatives.

Regarding measurement strategy, in order to obtain the blocked forces it will be necessary to measure operational velocities at carefully selected locations on the mounting during normal operation. These same measured data will allow the blocked forces, and hence characteristic power, to be obtained both at the top and the base of the mast. Furthermore, it will be possible to derive operational contact forces from the same data. Hence, whilst our clear opinion is that the in situ measurement of blocked forces at the top of the mast is the best way forward, the measurement approach will not exclude other approaches.

3.8.2 Variable source activity

A particular difficulty in source characterisation is variability of source behaviour during characterisation measurements. This issue is particularly relevant to MWTs because the mechanisms generating significant structure borne noise and vibration in buildings are not known. Under these circumstances it is necessary to create a multidimensional database of source characterisation data referenced to one or more operational states. For example when dealing with rotating machinery, the rotational speed is often used as the reference for each measured data set (Fyfe and Munck 1997). Sophisticated tools are available for this purpose. For the case of a MWT it may be more relevant to relate source strength to wind conditions.

As a starting point it may be assumed that for a given installation the structure borne sound power will depend on wind speed, as is the case for airborne sound power², simply because the running speed of a wind turbine will be greater during high wind. Another potential factor, not usually taken into account in airborne characterisations,

² BWEA Small Wind Turbine Performance and Safety Standard, Feb 2008.

is turbulence; this may also influence structure borne sound power delivery (wind speed and turbulence are discussed later). The issue of turbulence can also be taken to include gusts as large scale turbulence. Also for certain types of installation the wind direction may also play a part. Thus, since it is difficult to know at this stage the significance of turbulence and wind speed, it would be sensible to at least monitor these conditions if possible. Then, if the wind speed is found not to give a stable source characterisation, these other factors can be taken into account.

Based on the above, three different wind conditions may have to be taken into account: speed, direction and turbulence (taken to include gusts). This information can potentially be obtained from wind data monitored during the source characterisation measurements. An alternative, probably simpler approach, which is widely used for wind turbines is to plot noise generation versus power output. It is possible that the power will tend to normalise the effects of turbulence and gusts but this remains to be seen.

3.9 Conclusions

To conclude we reiterate that the in situ blocked force method appears to be the most suitable measurement method, arguably the only suitable method to be applied to MWTs. We also note that once blocked force data has been obtained it can be presented in a variety of ways: the most suitable format is the Characteristic Power which is the preferred parameter in EN12354-5 and which allows the complex mechanisms of vibration generation to be quantified in one neat parameter.

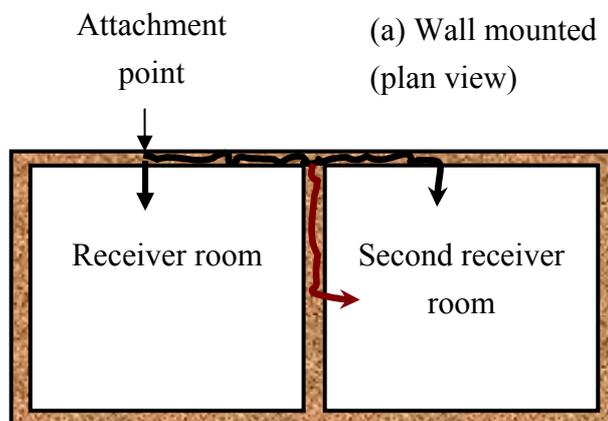
4 Transmission of structure-borne sound

In the previous section we reviewed methods for the characterization of structure-borne sound sources. In this section we deal with transmission through the building from the point where the MWT attaches to the building, to the receiver location. We also consider the role of the turbine mounting on transmission.

4.1 Worst case transmission path

It is helpful first to consider the worst case scenarios likely to be encountered which will generally be the room nearest to the point of attachment of the MWT. The owners of any MWTs will not be factored in as they have the ability to remove the turbine if there is a noise problem. The planning regulations are intended to protect occupants of neighbouring properties. However, in multiple dwelling buildings it is feasible that the MWT could be installed directly beside, or above, a neighbour's room. In fact, this situation arose in one of the case studies where complaints were received during Warwick Wind Trials as described earlier; in this case the owner of the MWT was the landlord of a block of flats and the neighbours were the occupants of the top floor flat. The worst case receiver locations are therefore as shown in Figure 13.

Figure 13 (a) also shows the possible transmission paths for sound and vibration into a second receiver room, i.e. via the façade or façade-party wall. In the case of a roof-mounted MWT, Figure 13 (b) illustrates that the transmission path for structure-borne sound is directly through the roof; but for vibration to be felt it would need to be transmitted to the walls, so via a minimum of one junction.



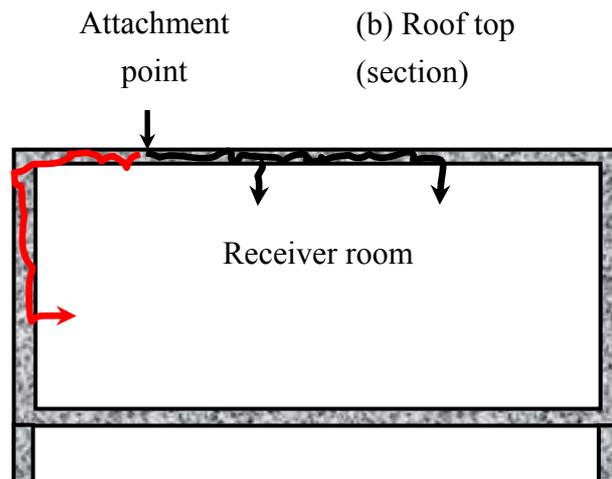


Figure 13: Schematic showing MWT and worst case receiver locations (a) wall-mounted (b) roof-mounted.

Thus, the transmission paths for the worst case receiver location are as summarised in Table 4 below.

Table 4: Worst case transmission paths

Mounting	Worst case transmission path
Wall-mounted	wall – room
Roof-mounted (for structure-borne sound)	roof – room
Roof-mounted (for vibration)	roof – junction – wall

For rooms further from the attachment point there will be more intervening junctions and hence, in general, greater attenuation and lower resulting sound and vibration levels at the receiver. In the next section we consider a method to calculate transmission.

4.2 EN12354-5: overview

A standard now exists which provides a prediction method for transmission of structure-borne sound through building structures, i.e. EN12354-5: 2009 (which has become a full, published standard since the start of this research. It is a complicated standard, dealing with the wide-ranging problem of noise from services equipment and which calls up no less than 21 other standards. The main sections of relevance to the structure-borne sound from MWTs are Section 4.4 and Annexes D, F and G. The prediction method is based on the injection of structure-borne sound power into the building by the source (the MWT in our case) and subsequent transmission through

the structure to a receiver room.

In broad terms the approach is:

- a The source is described by the Characteristic Structure-borne Sound Power, W_{SC} – (described in the Chapter 3);
- b The Installed Structure-borne Sound Power ($W_{s,inst}$) is the power actually injected into the building structure by the source – it is calculated from W_{SC} and an adaption term which takes into account the properties³ of the supporting element (in our case the facade or roof together with the mounting);
- c The transmission of sound from the point of attachment to the receiver room is then calculated for each possible transmission path, taking into account:
 - i the attenuation offered by intervening junctions, (see Figure 13)
 - ii the flanking sound reduction index for the building elements (see later)
 - iii the surface areas of the building elements involved (walls, floors etc)
 - iv the sound absorption in the receiving room.
- d The contributions of all transmission paths are summed to get the resulting sound pressure level in the receiver room.

The full prediction method in part 5 has not yet been subject to extensive field testing as a whole, indeed there is only one reported case study reported at Euronoise 2009 (Villot and Martin 2009) but for which there is no written paper. However, the third element in the above list, the transmission part of the chain, is largely based on earlier parts of the EN12354 series, in particular EN12354-1:2000 which has become quite widely used for calculation of flanking sound transmission in buildings. Therefore, some of the concepts employed in the prediction method have been in existence much longer than part 5 itself and have been tested in the field and the laboratory: these aspects will be reviewed in subsection 4.4.

In order to apply the prediction method to the case of MWTs the following data will be required:

- The Characteristic Structure-borne Sound Power of the MWT, W_{SC}
- The mobilities⁴ of the MWT and the supporting wall or roof
- The mobilities of the mounting system

³ The required property is the ‘mobility’: stiff, heavy walls and floor have low mobility and light-weight and flexible structures have high mobility.

⁴ stiff, heavy walls and floor have low mobility and light-weight and flexible structures have high mobility.

- Sound reduction indices, R_{ij} , for all walls, roofs or floors involved in the transmission
- The vibration reduction indices, K_{ij} , for any junctions on the transmission path
- The equivalent absorption area in the receiving room.
- The surface areas of walls and floors.

Possible sources of these data are given in Table 5.

Table 5: Data needed for prediction according to EN12354-5:2009

Component or building element	Data required	How obtained
MWT	Characteristic structure borne sound power	Measured (see Section 3)
MWT	Mobility	Measured
Supporting wall or roof	Mobility	Measured or estimated
Mounting system	Mobility	Measured or estimated
Walls/ floors/ roofs	Sound reduction indices, R_{ij}	Measured or from tables
Junctions	Vibration reduction factors, K_{ij}	Measured or estimated from EN 12354-1
Receiving room	Equivalent absorption area	Measured or estimated

4.3 Prediction of transmission through buildings using EN12354

In this section we summarise the methodology of EN12354 with respect to calculation of transmission of sound through building. The series of standards was first developed as a means of calculating flanking sound transmission in buildings, Part 1 dealing with airborne sound transmission and part 2 with impact sound. Flanking sound is that transmitted from a source to a receiver room by transmission paths other than directly through the party wall. Any flanking element, a wall, floor or ceiling can potentially provide a path for transmission. In this project we have a slightly different situation in that the building is excited directly by the MWT rather than by a sound source within a room. However, the transmission paths from the attachment point to the receiver room (as shown in Figure 13) are similar to flanking paths and can be evaluated using a similar approach. Hence, part 5 of the standard draws on the calculation procedures developed for flanking transmission in earlier parts of the standard.

The principles behind the transmission calculation are outlined in Eric Vigran's book *Building Acoustics* (Vigran 2008). The core of the approach is the prediction of a

transmission coefficient for each possible transmission path, i.e. the ratio of the sound power entering the receiver room via the flanking wall to that incident on the flanking wall in the source room. A final step, which is straightforward and does not require further explanation, is to sum the effect of all such flanking paths to obtain the total sound pressure in the receiver room. In what follows we explain how the transmission coefficients for each path are calculated.

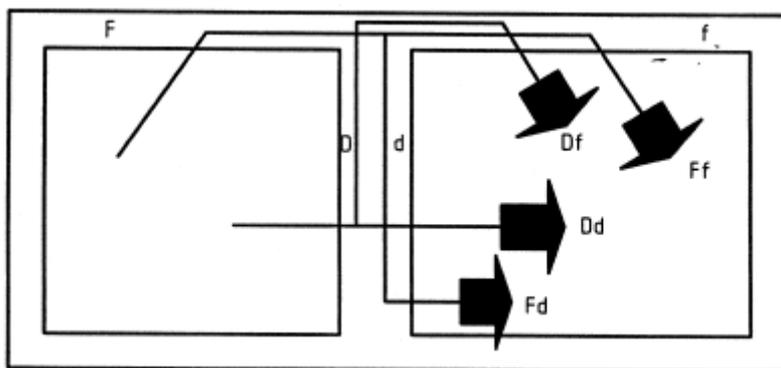


Figure 14: Flanking paths between a source and receiver room (from EN12354-1)

Shown in Figure 14 are one direct path (Dd) and three flanking paths between a source and receiver room. The flanking paths comprise:

- Sound enters the flanking wall F and is radiated from flanking wall f or party wall d;
- Sound enters the party wall D and is radiated from flanking wall f

According to EN12354 the transmission coefficient for each transmission path is calculated from:

- The sound reduction index of the two walls involved;
- The ‘vibration reduction index’ for the intervening junction, K_{ij} .

The question then arises as to where this data is to be obtained. One approach is to take measurements on an existing building and Annex F of EN12354-5 gives procedures for following this route. The measurement route provides a valid prediction methodology in cases where suitable data is not available. For example, it has been mentioned in Section 2.9 that there may be a difficulty in obtaining the appropriate properties for installations requiring local reinforcement at the connection points, such as timber frame or SIPs constructions as well as for steel frame structures. Using the measurement approach it would be possible to measure the transmission properties of an existing building and to plug this data into the prediction method so as to provide a prediction of sound and vibration levels prior to installation of the MWT. Clearly this would be more expensive than a paper-based prediction but

the possibility significantly increases the range of structures that can be handled.

The alternative to measuring the properties on an existing building is to try to obtain the data from existing databases and/ or prediction based. EN12354 provides some guidance in this respect which is discussed in the following.

Sound reduction index

Sound reduction index has been commonly used for many years: it is measured in the laboratory using ISO140-3 and most consultants have extensive databases of measured data. It is difficult to predict 'from scratch' but most consultants have procedures for adjusting measured data to new situations. In EN12354 there is also a procedure for including the effect of dry-lining or other linings.

Vibration reduction index, K_{ij}

The vibration reduction index describes the ability of the junction to prevent vibration (and sound) from being transmitted from one side to the other. EN12354 gives prediction formulae for seven common types of junctions. An example is shown in Figure 15. Note that the attenuation depends on the ratio of the mass per unit area of each of the plates but does not depend on frequency. These are based on theory by (Cremer et al. 1975, Gerretsen 1979, Gerretsen 1986, Kihlman 1967) who also compared with measurements. There is now a standardised procedure for measurement of the vibration reduction index in the laboratory (ISO10848). Not surprisingly, measured and predicted data do not always agree, and some case studies are reviewed in the following subsection.

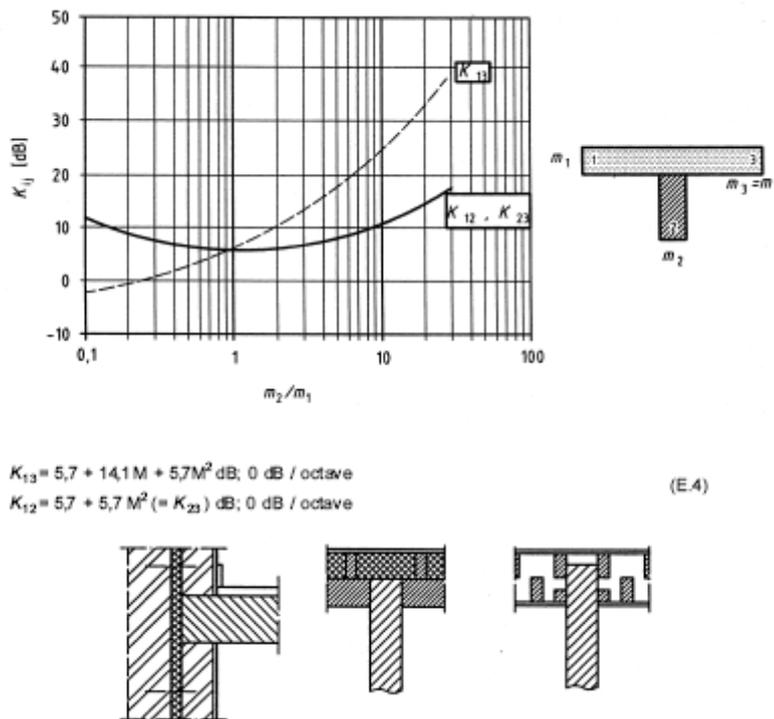


Figure 15: Example of vibration reduction index data for a rigid T junction from EN12354-1 Appendix E, with examples of junction

It has been pointed out by (Galbrun 2008) that the EN12354 approach to prediction of transmission is equivalent to a first order Statistical Energy Analysis (SEA) approach. This was also confirmed by (Nightingale and Bosmans 2003). Therefore, the approach can be considered to have a sound, if approximate, theoretical basis. The most important assumptions are essentially the same as that employed in most building acoustics work, i.e. the sound fields are assumed to be diffuse. In addition, it is assumed that the vibration field in the flanking walls is also diffuse. These assumptions mean that the method is limited in much the same way as is conventional building acoustics. Of particular relevance for this project is the limitation on frequency range: the accuracy is expected to deteriorate below 100 Hz where strong structural and acoustic modes may occur. It remains to be seen whether this frequency range will be important for the study although it seems likely that this will be the case as in (Dance et al. 2009) sound levels from a roof-mounted turbine are seen to peak at 63 Hz.

4.4 EN12354: review of case studies

In this section we review the basis of the methodology of EN12354 for predicting transmission, its limitations and accuracy. We also evaluate the degree of acceptance

within the acoustics community. This section does not claim to provide a comprehensive review of all literature associated with the standards, which is extensive, but only those elements relevant to this project.

(Galbrun 2008) compared predictions from the EN12354-1 method with those from and SEA model and with measurement. He found that level differences were over-predicted by around 5dB on average by the EN12354 method, i.e. the results are unconservative. He also comments that the quality of the predictions is heavily dependent on that of the input data. (Diaz and Pedrero 2004) found that predicted overall values of impact sound were within ± 4 dB of measured values for beam and pot floor constructions. Hopkins (Hopkins 2003) investigated transmission across a junction of masonry plates using measurement, FEM and SEA models. The third octave band level differences show 95% confidence intervals of typically ± 4 dB, and larger below 100 Hz. (Dolezal et al. 2008) tested the methodology on wood constructions and found reasonable agreement in overall values of predicted sound pressure of between 0 and 2dB. However, they caution that third octave band values show considerably wider variation and require more accurate modelling.

Other authors have considered the influence of constructions that depart from uniform homogeneous plates. Hopkins (Hopkins 2003) found, by measurement and FEM analysis, that the transmission of sound across a junction could be affected when the walls contain window apertures instead of being homogeneous plates as assumed in the theory. He found that a rule of thumb correction of 0, 1 dB or 2 dB can be applied depending on the configuration, but that the effect of windows at individual frequencies could be significantly greater than these figures. (Schneider and Fischer 2008) studied the loss factor in walls made of hollow brick. They concluded that the calculation models of EN12354, in which an in situ correction is applied, can be used for hollow bricks up to the first resonance of the brick. (Crispin et al. 2003) investigated application to double curtain walling constructions. (Villot and Guigou-Carter 2006) pointed out that an adaption term is required for lightweight constructions. Their proposal was tested by comparison of measurement and theory and provided good prediction accuracy.

(Metzen 1999) tested the accuracy of EN12354 predictions for 31 German constructions mainly consisting of heavyweight slabs. The difference between measurement and prediction was 2 ± 1.8 dB for the overall airborne sound insulation expressed as R'_w . (Pedersen 1999) performed a similar exercise with 200 Scandinavian constructions. The mean difference between measurement and

calculation was less than 0.5 dB with a standard deviation of less than 2.6 dB for monolithic constructions. The corresponding standard deviation for impact sound was 3.1 dB for monolithic constructions but the agreement was not considered satisfactory for lightweight constructions. A similar exercise was conducted by (Saarinen 2002) who found the mean and standard deviation of the difference between the calculated and measured values of nineteen facades to be 0.3+/-0.4 dB in laboratory conditions. Larger discrepancies were found in field conditions, the mean and standard deviation of the difference between the calculated and measured values of twelve facades being 3.8+/-3.8 dB. The larger discrepancy in field conditions was attributed to the fact that sound reduction index data was obtained by empirical estimation rather than measurement.

(Simmons 2007) collected the results of 40 measurements of transmission loss vertically through concrete slabs in real buildings and analysed each case according to EN12354. Across 26 comparisons the average difference between measured and predicted R'_w (airborne sound insulation) was 0.2 dB with a 90% confidence limit of 3.5 dB. For impact sound level ($L'_{n,w}$) the average difference was 1.9 dB and the 90% confidence limit was 5.1 dB. He states that the results are consistent with common experience that “a 3 dB margin is sufficient for most practical applications”. As a result of these tests he recommends a safety margin of 2 dB for predictions provided that good information is available about the constructions.

Table 6: Differences between measured and calculated sound insulation and impact sound level

Author	Mean, R'_w	Standard deviation	Mean $L'_{n,w}$	Standard deviation
Metzen	2	1.8		
Pedersen	0.5	2.6		3.1
Saarinen (lab)	0.3	0.4		
Saarinen (field)	3.8	3.8		
Simmons	0.2	3.5 (90% CI)	1.9	5.1 (90% CI)

The differences between measured and predicted sound insulation and impact sound level obtained by various authors are summarised in Table 6. There is reasonable consistency in the results considering that Simmons results are for 90% confidence intervals rather than standard deviation.

Another interesting finding from Simmons work is the variability in the results of the

calculation from different operators: he asked 4 operators to perform the same calculations and found significant differences between the results with standard deviation of 3 dB for R'_w and 2.6 dB for $L'_{n,w}$. The relatively large differences were assumed due to the inexperience of the operators, half of which had not previously performed such calculations. From this we can conclude that EN12354 predictions should only be performed by experienced personnel. It should be noted that in the cases looked at by Metzen and Simmons the direct transmission path was probably dominant and that errors in the flanking transmission paths could be larger: since the transmission paths to be dealt with in this project are essentially flanking paths some caution is needed in using Simmons suggested safety margins.

To summarise this section, there has been fairly extensive testing of the transmission calculation procedures of EN12354 parts 1 and 2. When good input data is available the discrepancies between measured and predicted single figure sound reduction index of monolithic constructions are generally less than 2 ± 2.6 dB. These discrepancies increase to 3.8 ± 3.8 dB with estimated input data. The differences are larger for impact sound. The agreement for lightweight constructions could be unsatisfactory, however an extended prediction methodology is available, albeit not yet standardised. The valid frequency range is down to 100Hz, below which prediction is possible but the accuracy is likely to worsen. This is most likely the reason for higher variance with impact sound predictions in which there is more emphasis on low frequency sound.

4.5 Prediction of vibration level with EN12354

As described above, the EN12354 method is aimed at predicting sound levels in the receiver room and thus is suitable for the structure-borne sound element of the project. However, we are also interested in tactile vibration. The EN12354 approach does not explicitly include vibration level in the flanking walls as an output. However, vibration level does appear as an intermediate step in the calculation, and therefore the approach can be adapted to include prediction of vibration level. The only issue with this approach might be concerned with the frequency range: humans are most sensitive to tactile vibration in the 10 Hz range which is below the frequency range normally considered for structure-borne sound. As explained earlier, we would expect more variance in the results at such low frequencies such that a wider safety margin will be required.

4.6 Characterization of mounting systems

In this section we consider how to characterise the mounting systems, taken to include

everything between the hub to the building, i.e. mast and brackets or mounting stand. There is expected to be some attenuation throughout this system but the question is how this may be characterised and how the data may be obtained.

EN12354-5 defines a coupling term, D_C , as the difference (in dB) between the characteristic power of the source and the power injected into the building structure. This quantity is intended to apply to small resilient elements, but there is no reason why it should not be extended to apply to the whole mounting system. This approach is convenient because it quantifies the attenuation in a single (frequency dependent) parameter. Both the required quantities, characteristic power and injected power are to be obtained for the test installations so in theory the coupling term can also be obtained. Some caution is advisable because, whilst the approach is theoretically sound, there are no published case studies and therefore the accuracy is unknown.

Also of relevance, is the series of standards relating to characterisation of mounting properties (ISO 10846 parts 1-4). Again, these are intended primarily for resilient mounts used for machines etc. and may not be readily adapted to apply to the whole mount. Nevertheless, these standards may prove useful in the event that rubber elements are to be replaced. Some estimate of the effect on transmission should be possible using data obtained according to these standards.

4.7 Discussion and conclusions

It can be seen from the above review that the EN12354 series of standards has been quite widely studied by numerous groups in a number of different countries. This is even clearer when we consider that at the recent Euronoise 2009 conference a special session was held in which 11 papers were presented from groups in 8 different countries, see for example (Villot and Martin 2009). This indicates that the approach is now quite widely accepted. Thus, in terms of obtaining wide acceptance of the results of this project it would seem sensible to follow the same approach where possible.

An important limitation on the EN12354 methodology is the frequency range – predictions will be subject to increasing uncertainties below 100 Hz which is evidenced by the greater errors in impact sound prediction. An alternative to the energy approach of EN12354 which might be more suitable for low frequency prediction is to use a transfer function approach. Here, the building would be characterised by a transfer function between the point of excitation (the attachment of

the MWT) and one or more points on the walls or floor of the receiver room. The approach has already been mentioned earlier with respect to source characterisation. Such transfer functions can be measured in situ for existing buildings and predictions based on measured transfer functions would be expected to be reasonably accurate. The disadvantage is that the transfer function measurement requires specialised expertise and equipment.

It is feasible to predict such transfer functions using FEM models (see for example Hopkins 2003), and indeed such an approach is recommended in ISO14387 for prediction of structure-borne sound and vibration from rail systems. The main disadvantage is that numerical modelling requires facilities and expertise which is beyond the means of all but some of the larger consultancies. There are no simple, standardised methods of prediction i.e. there is no equivalent to EN12354 suitable for predicting building transfer functions at lower frequency. One possible way round this would be to make available a data base of transfer functions describing a limited range of scenarios such as the worst case transmission paths as described above. It may prove feasible to limit the range of variables sufficiently to allow a meaningful data base of transfer functions, probably based on measurement, to be formulated. The aims of such a database could sensibly be limited, for example to allow prediction of worst case scenario rather than providing a full numerical prediction of expected level (this ‘scoping’ approach is suggested in ISO14387).

How to characterise the mounting system is probably the least clear aspect of the proposed prediction procedure at this stage. However, the ‘coupling term’ defined in EN12354-5 provides a consistent way forward. A fallback position is also available, i.e. to lump the mounting system in with the turbine and to treat the whole assembly, turbine-mounting as the source. The disadvantage would be that different source strength data would have to be provided for different mounting arrangements, but at least this would provide a way forward.

As a final comment, the state of the art is not sufficiently advanced to allow us to rely solely on prediction methods to quantify the transmission of structure-borne sound and vibration through buildings. Therefore, some support from measured data will be required.

5 Relevant noise and vibration criteria

The purpose of this project is to produce a prediction methodology: this does not include developing criteria for acceptable noise and vibration. Nevertheless, it is important to understand existing criteria so that the prediction method can produce data in an appropriate form for comparison. In particular, since various averaging times are used for noise and vibration criteria it is important that the prediction method provides compatible outputs. Therefore, the main purpose of this section is to determine the range of indicators, time and frequency averaging parameters likely to be used to assess acceptability of noise and vibration.

Potential impacts on people include the following existing criteria for which are discussed in the following four subsections:

- annoyance due to structure-borne sound
- annoyance due to tactile (feelable) vibration
- annoyance due to rattling of fixtures and fittings cause by sound or vibration
- damage to buildings due to vibration.

5.1 Structure-borne sound

In this section we consider criteria for structure-borne sound, i.e. sound transmitted directly from the MWT through the building structure to the receiver location (usually in a room). Sound levels depend on various factors and it is necessary to consider the following:

- The measurement indicator
- The time period over which the assessment is to take place
- The frequency weighting
- The measurement location.

5.1.1 BS4142: 1997 and other UK provisions

Probably the most common method in the UK for predicting the likelihood of complaints due to noise from machinery is BS4142: 1997. The likelihood of complaints is said to be related to the amount by which the noise from a new source exceeds the pre-existing background noise at the location. Thus, there is no fixed limit but the amount of noise that can be tolerated from a new noise source is considered to depend on the noise levels already present in the neighbourhood. This principle is widely accepted in the UK; however BS4142 cannot be applied in the case of micro-turbines because the assessment is carried out at an external location outside the façade of the affected property. External assessment is a sensible approach for most

source of environmental noise, but in the case of building-mounted equipment sound is transmitted directly through the walls and into internal spaces. Therefore, for this project it is only relevant to carry out the assessment at an internal location and BS4142 cannot be applied.

Other planning and enforcement tools are available to local authorities in the UK for dealing with noise issues. One such document is the Noise Act 1996, introduced primarily to deal with noise from entertainments, late night parties etc. but which could potentially be applied to MWTs operating during ‘night hours’, defined as between 23:00 and 07:00. The Act specifies that noise measurements should be made in terms of a 5 minute average noise level, $L_{Aeq,5 \text{ minutes}}$.

5.1.2 BS8233: 1999 and WHO guidance

Guidance on the suitable levels of internal sound is given in Table 5 of BS8233: 1999. Unlike BS4142, the guidance does not take into account the pre-existing background noise but recommends absolute levels for inside dwellings. The criteria of most relevance for this project are those for bedrooms and living rooms which are given in terms of a time-averaged $L_{Aeq,T}$. The averaging time is not specifically given but it is normally assumed to be over the day or night for living and bedrooms respectively. The criteria are reproduced in Table 7 (similar levels are also given in WHO 1999). Also given in a footnote is a criterion for bedrooms based on a maximum level (with the sound level meter set to ‘fast’ averaging time). Therefore, if using these criteria to assess the acceptability of internal sound levels the prediction method will need to produce both long term (daily and or nightly) average sound levels ($L_{Aeq, T}$) and maximum levels ($L_{Amax,F}$).

		Design range $L_{Aeq,T}$ dB	
		Good	Reasonable
Reasonable resting/ sleeping conditions	Living rooms	30	40
	Bedrooms ^a	30	35
^a For a reasonable standard in bedrooms at night, individual noise events (measured with F time-weighting) should not normally exceed 45 dB L_{Amax} .			

Table 7: Indoor ambient noise levels in spaces when they are unoccupied as given by BS8233:1999.

No guidance is given as to the position of measurement within the room.

The above levels have been derived on the basis of ‘anonymous’ noise sources such as road traffic and it should not necessarily be assumed that they are good predictors

of disturbance for structure-borne sound from building-mounted wind turbines which are expected to produce sound of a more distinct character.

5.1.3 Guidelines for rail noise and vibration

ISO14387: 2005 does not provide numerical criteria for ground-borne noise as such, referring instead to national criteria. However, it does advise the indicator to be used: the maximum A-weighted sound pressure level with a slow time constant, L_{pASmax} is advised. Furthermore it advises that the raw unweighted sound pressure time history should be preserved so that metrics such as event L_{pAeq} and the one-third-octave band spectrum can be derived. Regarding measurement position it advises that measurements should be taken near to but not at the centre of the room in order to avoid standing wave effects.

The US Federal Transit Administration (Federal Transit Administration 2006, see also Federal Railroad Administration, 2005) provides criteria for acceptable levels of groundborne noise from rapid transit systems in three categories of buildings. The criteria for 'Residences and buildings where people normally sleep' are:

35 dBA : Frequent events (>70 per day)

43 dBA : Infrequent events (<70 per day)

The report states that the above criteria are 'maximum levels for a single event' although no time constant is given. If we assume a 'fast' time constant then these levels can be taken as maximum allowable $L_{Amax, F}$ levels.

There are some differences between the character of groundborne noise from rapid transit systems and that expected from MWTs which means that the above criteria should be applied with caution. First, the FTA limits are said to be based on experience from rail transit systems where the exposure is primarily derived from individual events with typical duration less than 10 seconds. This differs from that expected from MWTs where the sound could be more or less steady over periods of minutes or hours. On the other hand, the same limits are also recommended for freight trains, where much longer events are expected. Secondly, groundborne noise from railways is transmitted through the ground and into buildings via foundations whereas the structure-borne sound from MWTs is via excitation of the building walls or roof: these different transmission paths may result in different frequency content of the two types of signals as perceived internally.

No separate criteria are given for day and night exposure in the FTA guidelines, but since the building category is given as ‘residences and buildings where people normally sleep’ it seems reasonable to assume that the limits are intended to be applied at night. We may note that the ‘infrequent events’ criterion of 43 dBA is quite close to the maximum value for individual noise events at night of 45 dBA from BS8233. Furthermore, whilst we cannot strictly compare different indicators without knowledge of the time dependence, we can argue that in practice the 35 dBA maximum limit from the FTA for frequent events is probably not inconsistent with the 30 dBA ‘good’ criterion for steady sound from BS8233. Therefore, although stated in a different way, in practice the US guidelines are probably fairly similar to those used in the UK.

Earlier guidelines by the FTA and also by the American Passenger Transport Association (APTA) are reviewed in the ANC Guidelines (Association of Noise Consultants, 2001). In the same guidelines are mentioned criteria of 35 dB $L_{Amax,F}$, set by local authorities in London and South East England for the Channel Tunnel rail link, and 40 dB L_{Amax} (no time constant given) adopted by London Underground as a complaint threshold.

L_{Amax} is used consistently in the above criteria by the various authorities. However, since train noise is more event-based than MWT noise the same metrics are not necessarily appropriate.

5.1.4 Averaging time

The above criteria can be classified as those applying to steady sound and those relevant to sound from individual events. At this stage we anticipate that under steady wind conditions the sound from MWTs will be predominantly steady, in which case a time-averaged noise indicator ($L_{Aeq,T}$) will be appropriate. However, under gusty conditions it remains to be seen whether an ‘event-based’ approach might be more suitable in which case we would require the maximum noise level for comparison with the above criteria. Prior to results coming available it seems sensible to leave open the possibilities of evaluating both the average and maximum levels.

Regarding average levels, the time over which the average is taken needs to be carefully considered. The criteria for continuous noise from BS8233 and WHO are presumed to be based on 8 hour night-time and 16 hour day time periods. However, the implication is that these criteria apply to ‘anonymous’ noise sources such as road traffic where hour by hour differences in noise level during the day or night tend to be

marginal. On the other hand, MWT noise could differ considerably in that wind conditions and hence noise levels could vary significantly hour by hour over the day or night periods. Therefore, we could argue the noise source is neither strictly steady (requiring a long assessment period) nor event-based (requiring a short period) but somewhere in between. In BS4142, which applies to industrial rather than transportation noise, averages are taken over 1 hour during the day and 5 minutes at night. This approach is somewhere between a continuous and event-based approach and gives more emphasis to short, noisy periods at night.

The permitted development rights for small scale renewable technologies (CLG, 2009) includes a specific recommendation for airborne sound from wind turbines:

The noise level from the installation must not exceed 45dB $L_{Aeq, 5 \text{ min}}$ at 1 metre from the window of a habitable room in the façade of any neighbouring residential property (but ignoring the effect of that façade).

The actual levels cannot be adopted directly for structure-borne sound because they refer to external positions. However, the use of a 5 minute L_{Aeq} is consistent both with the BS4142 approach for night time and with the Noise Act 1996. Bearing this in mind, together with the above discussion, it seems sensible to adopt the same approach. Therefore, both for consistency with existing permitted development rights and UK legislation we propose that assessment be conducted in terms of a maximum $L_{Aeq, 5 \text{ minutes}}$.

5.1.5 Low frequency noise

It should be noted that all the above suggested criteria make use of ‘A’ weighted measurements (indicated by the subscript ‘A’). This means that a filter is applied to the measurement so as to mimic the frequency response of the human ear. This is standard practice for measurement of environmental noise. However, it is widely acknowledged (see for example WHO 1999) that ‘A’ weighted indicators may be inappropriate if the sound includes significant low frequency content. For example, sounds that might be described as ‘rumble’, ‘hum’, ‘boom’ etc. may contain a predominance of low frequency sound energy, such that the usual ‘A’ weighted indicators, including those mentioned above, could underestimate potential disturbance. The German standard (DIN45680) provides a method for assessing whether the sound at a given location should be classed as a low frequency sound: a difference of 20 dB or more between the ‘A’ weighted and ‘C’ weighted sounds levels indicates that further investigation is required. At this stage we do not know whether

structure-borne sound from WTs needs to be classed as low frequency sound but the possibility needs to be kept open until the above test can be applied in real situations.

Should MWTs be found to produce significant low frequency sound in attached dwellings then it will be advisable to consider a low frequency sound criterion. Such criteria have been adopted in several countries around the world (Germany, Denmark, Sweden, the Netherlands, Poland, Japan, UK and Australia). In the UK guidance, a criterion curve is provided in third octave bands in the low frequency region (see Figure 16). This approach is similar to that used most other countries with the possible exception of Denmark, where a single ‘low frequency dBA’ criterion is in use.

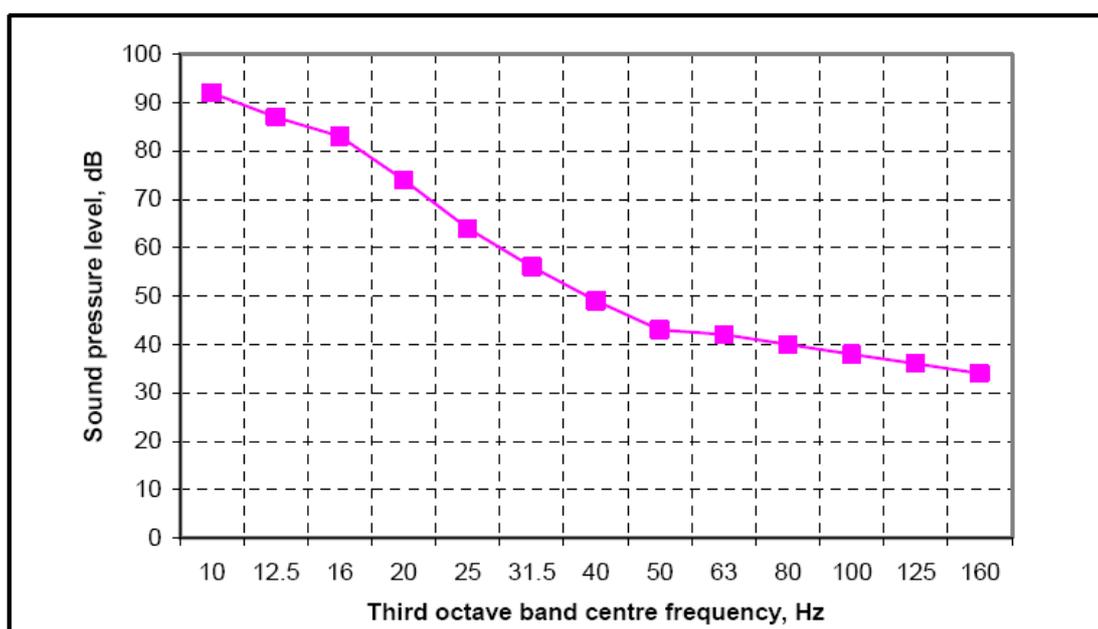


Figure 16 Criterion curve for the assessment of low frequency noise (from Moorhouse et al. 2005)

Measurement position is important for low frequency noise since the levels may vary significantly throughout a typical room. UK guidance recommends to measure at a position where the complainant says they can hear the noise. However, this is intended for analysis of existing complaints and is not relevant for prediction purposes. Guidance from other countries suggests using either a corner position (which would tend to give a maximum value) or an average throughout the room. The situation is complicated even further because several different methods have been proposed to obtain an average.

5.1.6 Conclusions on criteria for structure-borne sound

There are no existing noise criteria which can be applied directly to structure-borne sound from the MWTs. The above discussion suggests that a 5 minute averaged, ‘A’

weighted sound level ($L_{Aeq, 5 \text{ minutes}}$) would be most appropriate, which is also consistent with existing approaches for industrial noise and for permitted development rights. For assessment according to the above criteria the proposed measurement position is close to, but not at the centre of the room.

However, at this stage it is not known whether a single ‘A’ weighted criterion will be sufficient or whether additional criteria for low frequency noise will be required. The low frequency noise criteria would place additional demands on the measurement and processing, in particular by requiring additional microphone positions in the receiving room. This aspect of the measurement proposal requires further analysis once data starts to become available from the source characterisation tests in WP2.

Finally, it should be mentioned that in view of the variety of criteria in use we consider it advisable to measure full time histories during the MWT characterisation tests so that any combination frequency and time weighting can be extracted during later analysis. Fortunately, provision for such has already been made during the proposal.

5.2 Annoyance due to tactile vibration

The permitted development rights proposal (CLG, 2009) includes consideration of potential disturbance due to vibration from MWTs. The aim of this section is to review suitable criteria. We need to consider similar issues to those considered for structure-borne sound in the previous section, i.e.:

- The measurement indicator
- The time period over which the assessment is to take place
- The frequency weighting
- The measurement location.

ISO 14387: 2005 (relating to rail systems) states that “*human perception and whole-body response to vibration inside buildings should be based principally on the overall (and running) r.m.s. frequency-weighted acceleration in the three orthogonal directions*”. However, no numerical criteria are provided as such, instead it is simply stated that measurements should be consistent with national standards. The standard provides some advice on data collection, stating that measurements should be made at the centre of floor spans. It also refers to ISO 2631 parts 1 and 2 (see later).

In the UK, BS6472: 2008 says it provides the “*best available information on the application of methods of measuring and evaluating vibration in order to assess the*

likelihood of adverse comment". The approach is to evaluate 'vibration dose values' (VDV) which evaluates the accumulated vibration 'dose' throughout the day (16 hour) or night (8 hour). Thus, VDV has some similarities with the idea of accumulated noise or radiation dose for workers, except that it is used to evaluate annoyance rather than health effects. In this way intermittent, impulsive and time-varying vibration can be evaluated on a consistent basis with continuous vibration.

The frequency range is restricted to 0.5-80 Hz, and separate frequency weightings are required for vertical and horizontal vibration, W_b for vertical and W_d for horizontal⁵. These frequency weightings show that the maximum sensitivity occurs in the frequency range 4 - 12.5 Hz for vertical and 1 - 2 Hz for horizontal acceleration. In both cases this is a considerably lower frequency than for structure-borne sound, and this fact has potentially significant implications for the accuracy of the prediction method as mentioned earlier.

Regarding measurement position, BS6472 states that vibration sensors should be placed as close as possible to the 'point of entry' to the human body, generally a position on the floor with the maximum expected acceleration (likely to be mid span – the advice is therefore consistent with that from ISO 14387 mentioned above). It is recommended that full unweighted vibration recordings be made in three perpendicular axes (two horizontal, one vertical). BS8041: 2005 is referenced for a fuller description of measurement instrumentation, and practical guidance is given in the ANC Guidelines (ANC 2001).

The VDV approach is widely accepted by consultants but can be difficult for non-specialists to follow particularly because of the unusual units. Also, working with VDV's over 8 or 16 hours is considerably less convenient than working with, for example, a 5 minute L_{Aeq} as has been suggested for structure-borne sound above. Furthermore, it is difficult to envisage how a simple rating for a particular model of MWT, as might be used on a label for example, could be provided in terms of VDV. Therefore, a simpler approach would be convenient if such could be found. One possibility might be to work on the basis of the threshold of perception for vibration. BS6472-1:2008 advises that about a quarter of the population will perceive vertical vibration with an acceleration greater than $0.01 \text{ m}\cdot\text{s}^{-2}$ (frequency weighted using the W_b weighting) when standing or seated. It further advises that, in homes, adverse

⁵ These frequency weightings can be considered as equivalent to 'A' weighting.

comment may start at levels only slightly higher than the threshold of perception. Therefore, a reasonable guide to the onset of adverse comment would be to apply this figure for the perception threshold as a maximum for the weighted vertical acceleration.

5.2.1 Conclusions for tactile vibration

Current standards in the UK assess the possibility of adverse comment on the basis of a vibration dose value (VDV) over 8 hours (night) or 16 hours (day). This approach is widely accepted but is not particularly convenient for the simple output we are aiming for with respect to permitted development rights. A simpler, but more conservative, approach might be to work on the basis of threshold of vibration perception.

As is the case for structure-borne sound, various possible indicators could be used and so it would be wise to record unweighted acceleration time histories during the source characterisation tests (WP2), so that any combination can be extracted in later analysis. This is particularly the case because work is currently ongoing (funded by Defra) to derive dose-response relationships for vibration annoyance which may provide additional or alternative acceptance criteria.

5.3 Structural damage due to vibration

One case of building damage was reported during the Warwick Wind Trials. It is our belief that this was caused by wind loading (quasi static) rather than by vibration. However, in the absence of definitive information it would be prudent to evaluate criteria for building damage.

ISO 14837 states that most damage occurs in the range 1-150Hz. It also states that the vibration levels required to cause damage are of the order of 10 to 100 times larger than those associated with human perception and thus levels of vibration sufficient to damage a building, even cosmetically, would be intolerable to occupants. This suggests that the criteria for human perception as mentioned above will be the limiting factor for vibration rather than building damage.

Table 8, reproduced from the ANC Guidelines (ANC 2001) and in turn from BS7385-2, provides guide values for cosmetic damage. The values are given in terms of peak particle velocity (ppv). This is a different parameter entirely from those discussed above for tactile vibration and will require different processing of the vibration data collected.

BS7385-1 (ISO 4866: 1990) provides guidance on measurement locations but which

are specific to groundborne vibration and not applicable in this case. The ANC Guidelines (ANC 2001) recommend measurement at the foundation or load-bearing wall, which again implies the source of the damaging vibration is groundborne which does not apply to our case. In order to capture the maximum vibration level we therefore propose to measure or predict the vibration amplitude (ppv) at the point of attachment of the MWT.

Table 8: Transient Vibration Guide Values for Cosmetic Damage

Line	Type of building	Peak component particle velocity (mms ⁻¹) in frequency range of predominant pulse	
1	Reinforced or framed structures Industrial and heavy commercial buildings	50 at 4 Hz and above	
2	Unreinforced or light framed structures Residential or light commercial type buildings	4 Hz to 15 Hz	15 Hz and above
		15 at 4 Hz increasing to 20 at 15 Hz	20 at 15 Hz increasing to 50 at 40 Hz and above

To conclude, we believe that reported cases of building damage were most likely due to (quasi static) wind loading rather than to vibration. This type of loading should normally be assessed by a structural engineer prior to installation of a MWT and will not be evaluated during the project. However, we do propose to evaluate the possibility of building damage being caused by vibration. The proposed approach is to evaluate the peak particle velocity (ppv) at the point of attachment of the MWT. Criteria for building damage are considerably less stringent than those for tactile vibration which suggests that the latter will provide the limiting requirements.

5.4 Rattling

In ISO14837-1: 2005 the secondary effects of vibration are considered as a separate category to ground-borne noise. It is stated:

“Secondary effects include higher frequency noise emitted by rattling of some items such as glasses, dishes, windowpanes, ceilings, light fittings and some furniture. Guidance is not provided on the prediction of sound generation by this mechanism because it is difficult to quantify, although it can be a significant source of disturbance.”

Whilst this standard is primarily concerned with noise and vibration from rail systems the mechanisms are similar for MWTs and we might therefore consider it wise to

include a criterion for rattling. However, no criteria are provided within ISO14837.

In the Transportation Noise Reference Book (Nelson 1987) it is pointed out that an acceleration of greater than 1g (10ms^{-2} peak) is theoretically required to cause rattling of objects resting on horizontal surfaces (this is because the object would ‘lift off’ the surface once per oscillation). This is a high acceleration level unlikely to be encountered in practice. However, many objects are suspended and rest against vertical surfaces, for example pictures, mirrors, plaques, lamps etc. In such cases the contact with the supporting wall is often at a few discreet points and separation, and hence rattling, can occur at much lower levels of vibration. Consequently, it is recommended that a criterion of 0.05g (0.5ms^{-1} peak) be adopted to prevent rattling (Hubbard 1982). This should apply theoretically to situations where the hang angle (angle between wall and hanging flat object) is about 3° . However, the cross hatched area in Figure 17 (Hubbard 1982) indicates measurements from situations where rattling had been reported. The scatter of measured results suggests that small variations in the wall geometry or that of the suspended object can be significant. By implication, objects that hang by smaller hang angles are susceptible to rattle at lower acceleration levels.

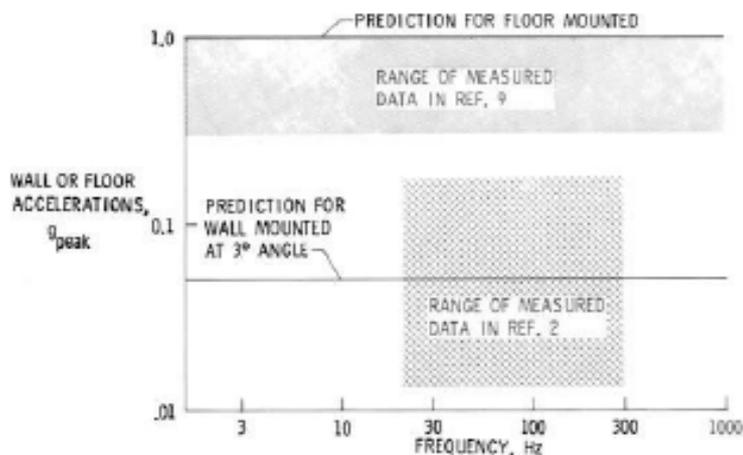


Figure 17: Criteria for the rattling of wall and floor mounted objects (from Hubbard 1982)

It is worth noting that the criteria for rattling are generally higher than those for tactile vibration. This suggests that, for a subject in contact with the wall or floor causing vibration, they would tend to feel the effects more readily than they would hear rattling. However, it is possible to conceive of some cases where the subject is not in physical contact with the same wall in which case it is advisable to retain criteria for rattling.

In Japan, criteria are available for avoidance of rattling (Kamigawara 2006).

However, these deal with the case where the rattling is induced by low frequency noise (e.g. from aircraft) rather than from direct excitation of the structure as we have in this case. Therefore, it is not possible to apply these criteria directly in this project.

In conclusion, a simple criterion is available for avoidance of rattling caused by vibration, although this does not appear to have been subject to rigorous checks and is not referred to by more recent standards. It is however less stringent than the criteria for tactile vibration suggesting that rattling may not be the limiting factor.

6 Proposed prediction methodology

In this section we outline our proposals for the prediction methodology. The approach remains essentially the same as in our proposal (University of Salford 2009) but with some additional details in the light of the above discussions.

The prediction methodology should be as simple as possible. The final methodology is likely to be a compromise between simplicity and accuracy. Achieving an appropriate balance is one of the major challenges of the project.

In what follows we first give an outline of the approach, then discuss proposed outputs from the prediction methodology, followed by a description of how to obtain the required input data.

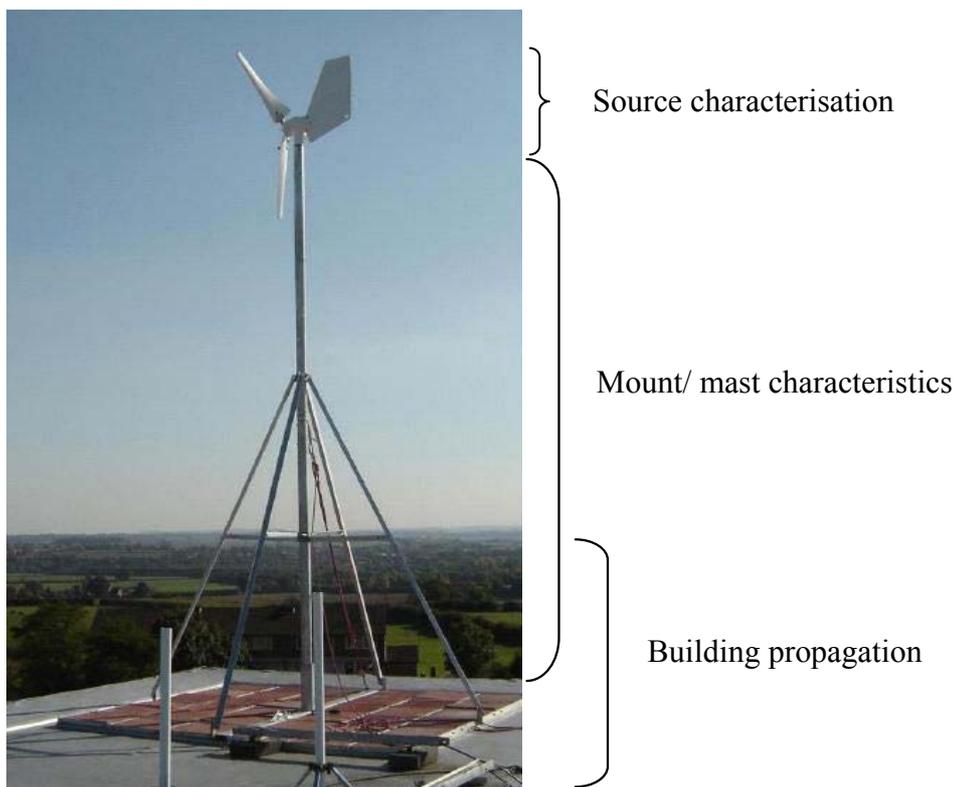


Figure 18: Proposed subdivision of the generation and transmission path

6.1 Outline of the approach

It is proposed to treat the problem in three parts, turbine, mounting and building, as shown in Figure 18. The prediction procedure broadly follows the approach of EN12354-5 with extensions for tactile vibration. An extension may also be required to cope with low frequencies. The main steps in the procedure for prediction of

structure-borne sound are as follows:

- a. The MWT is characterised by the ‘Characteristic Power’
- b. The power injected into the building is calculated from the Characteristic Power, the attenuation of the mounting and the properties of the building structure
- c. The transmission through the building to the receiver location is calculated taking into account the properties of walls/ floors and junctions in the transmission path
- d. The sound pressure in the receiver room is calculated from b and c.

Extension to low frequencies

The above approach represents current best practice for the frequency range down to 100 Hz. For lower frequencies the variance in the prediction is likely to increase. Therefore, if lower frequencies prove to be of particular importance it may be necessary to supplement the above power-based approach with an approach based on applied forces rather than power. This would be compatible with the above and would follow essentially similar steps:

- e. The MWT is characterised by the ‘Blocked Force’
- f. The forces applied to the building are calculated from the Blocked Forces, the attenuation of the mounting and the properties of the building structure
- g. The transmission through the building to the receiver location is calculated taking into account the properties of walls/ floors and junctions in the transmission path.
- h. The sound pressure in the receiver room is calculated from f and g.

Extensions for tactile vibration and rattling

For prediction of tactile vibration a slight modification will be required in the calculation of transmission but otherwise the treatment will be the same.

Building damage assessment

For building damage assessment we propose to calculate peak particle velocity from the blocked forces of the MWT and the mobility of the building at the attachment points.

6.2 Prediction method outputs

We propose that the prediction method should provide outputs consistent with the most commonly used criteria. These are summarised in Table 9.

Table 9: Proposed outputs for the prediction methodology

Output	Parameter	Position	Frequency range	Evaluation time
Structure-borne sound	$L_{Aeq,5 \text{ minutes}}$	Near room centre	To be determined	5 minutes
Tactile vibration	VDV	Centre of floor span	1-80 Hz	8 hours night 16 hours day
Building damage	Ppv	Point of attachment to building	1-150 Hz	Instantaneous
Rattling	Peak acceleration	Walls in receiver room	To be determined	Instantaneous

6.3 Input data for prediction methods

The ‘source’ will initially be defined as the turbine itself, excluding the mast and mounting. Therefore, to implement the prediction methodology will require data pertaining to:

- Source characterisation
- Mounting attenuation
- Building transmission

which are discussed in the following sections.

6.3.1 Source characterisation data

The proposed measurement method is the in situ blocked force method which has two major advantages:

- it can be implemented in a normal installation operating in representative conditions
- the blocked force data characterises the MWT independently of the mounting and supporting structure.

Measurements

The in situ blocked force method requires measurements of acceleration to be made at 10 or more locations on the mounting. These will be made with accelerometers (see Figure 19). Measurement locations will include the base of the mounting where it attaches to the building.

In addition, we will require measurements of mobility which will be made with a force hammer.

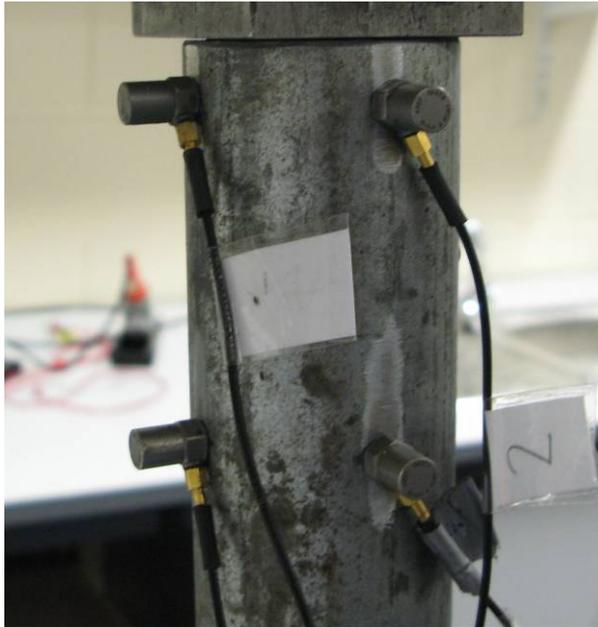


Figure 19: Illustration of accelerometers attached to MWT mast

Accelerations at all positions will be monitored simultaneously over several weeks of normal operation in order to capture a range of wind conditions.

We also propose to make simultaneous measurements of:

- Wind speed and direction
- Turbulence intensity
- Rotation speed (possibly)

Form of data

As is clear from the above discussion, a sophisticated measurement and analysis approach is required to achieve reasonable accuracy. However, we will aim to make the source characterisation results available to a wider audience in the form of a databases in an easily accessible format designed for download. As far as possible this will be consistent with the Acoustic Noise Label defined in the BWEA Small Wind Turbine Performance and Safety Standard. The likely form of the data will be plots of tables of Characteristic Power in third octave bands, plotted against wind speed, or preferably, turbine power. This form is similar to that used for the sound power of wind turbines and will therefore be readily understood.

In order to further improve accessibility to the data we propose to investigate presenting the data in the form of noise and vibration levels in a 'reference installation'. For example, a particular model of MWT could be characterised by the levels of sound and vibration it would cause in a neighbouring bedroom in a typical solid brick construction. Data in this form would be easily understood by non-

specialists because it relates to the experience of residents. We would then need to supply a method for correcting the levels for other building and mounting types.

6.3.2 Mounting attenuation data

The attenuation of the mounting system will be characterised by the transmissibility, which is defined as the ratio of velocity (or acceleration) at the top of the mount to that at the bottom when the mount is excited from below. This data will be obtained primarily by laboratory measurements on each of the mounting systems, supported by calculation on simple models where appropriate.

It is a relatively advanced exercise to obtain this data, but once obtained it should be readily understood and incorporated into a prediction method.

6.3.3 Building transmission data

The building transmission characteristics will be defined by frequency response functions. These characteristics can be obtained in a several ways - in order of decreasing accuracy and increasing convenience:

- Measured on the actual building
- Calculated from the properties of the building elements using measured data
- Calculated from the properties of the building elements using estimated data
- Compiled from measured data on similar buildings (Figure 20 gives an illustration of how such data could be presented)

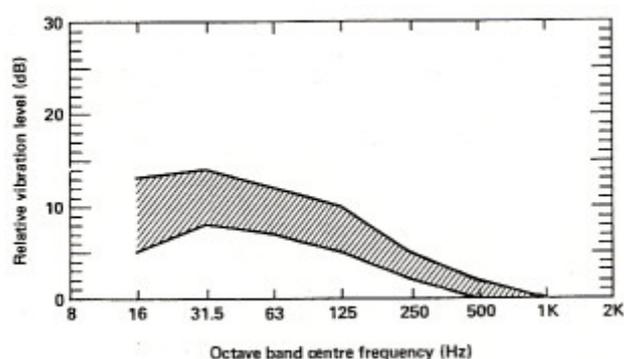


Figure 20: Example of transfer function data compiled from measurements on a range of buildings (From Nelson 1987)

Measured data on the actual building will be used during the study in order to obtain the most reliable data to validate prediction methods.

The optimum method to be used for the prediction method will depend on the accuracy that can be achieved. The simpler the method the better in terms of accessibility provided sufficient reliability can be achieved.

7 References

7.1 Standards

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8 Acknowledgement

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Appendix: theory for structure-borne sound sources

Consider an arbitrary structure borne sound source and an arbitrary receiver structure as shown in figure (A.1).

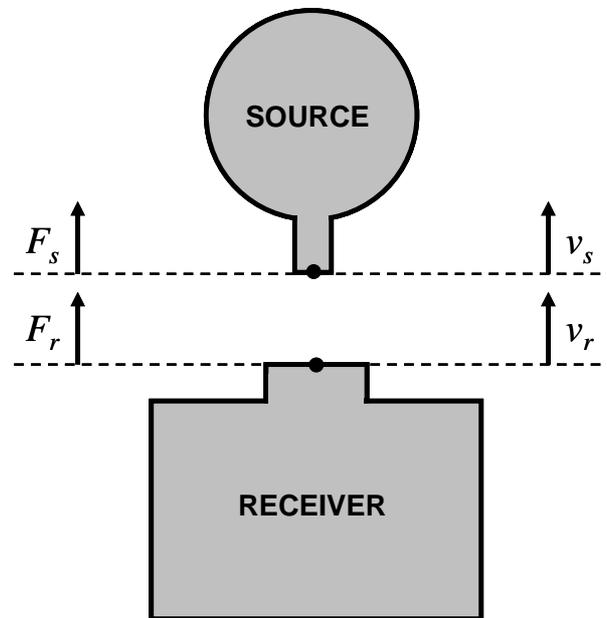


Figure (A.1): Arbitrary source and receiver structures. The ● marks the contact point on both the source and receiver structures. It is for these points which the forces and velocities F and v are defined.

Whilst uncoupled the source and receiver can be described so they are independent from each other using mobility relationships

$$v_s = Y_s F_s \quad (\text{A.1})$$

and

$$v_r = Y_r F_r \quad (\text{A.2})$$

where v and F denote force and velocity respectively which can be related to each other by the frequency response function, mobility Y . The subscripts s and r are used to denote source and receiver respectively. In this form source and receiver are described independently because no terms relating to the source occur in the relationship describing the receiver and vice versa. Equations (A.1) and (A.2) describe the passive properties of the source and receiver only.

When the source operates, forces inside the source will result in a velocity at the contact point so that,

$$v'_s = Y_{EI} F'_I + Y_s F'_s \tag{A.3}$$

Now the velocity of the source's contact point is defined in terms of an internal force F_I and an external force F_s and the mobility Y_{EI} relates the internal force to the external contact velocity. The dashes applied to the forces and velocities in equation (A.3) are used to show that the source is now active.

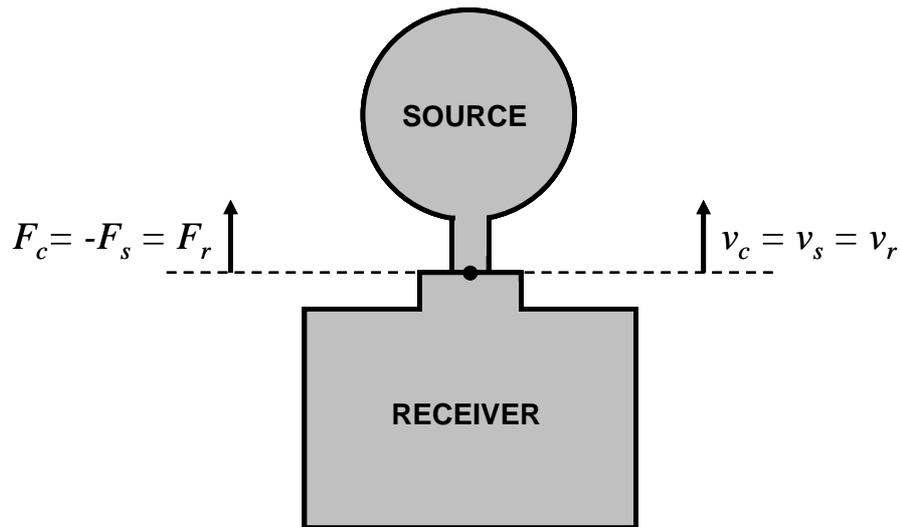


Figure (A.2): Arbitrary source and receiver structures coupled at a single point marked by •. The velocities of the source and receiver at this point are equal. The forces on the source and receiver at this point are equal and opposite.

Figure (A.2) again shows the arbitrary source and receiver structures which are now coupled. When coupled the velocities of the source and receiver structures at the point of contact must be equal. The forces on source and receiver at this same point must be equal and opposite however. The subscript c is introduced to denote coupled so that v_c is the velocity of the coupled source and receiver and F_c is the contact force which is defined as being equal to the force on the receiver. Using equations (A.1) and (A.2) it can be shown that the passive properties of the assembly can be described by,

$$\frac{1}{Y_c} = \frac{1}{Y_s} + \frac{1}{Y_r} \tag{A.4}$$

where Y_c is the mobility of the assembly at the interface.

Equations (A.3) and (2) can also be rewritten in terms of the coupled velocity v_c and

contact force F_c to describe the behaviour of the assembly when the source is active.

$$v'_c = Y_{EI} F'_I - Y_s F'_c \quad (\text{A.5})$$

$$v'_c = Y_r F'_c \quad (\text{A.6})$$

Again the dash is used to indicate that the source is operational. It is assumed that the mobilities do not change when the source is operational and so, they do not carry the dash. Equations (A.4) to (A.6) describe the passive and active properties of the assembly at the contact point only. Typically however one will be interested in the response at a further point or points which may be, for example vibration velocities or sound pressures. Finally therefore, we introduce a further generic frequency response function H_r for the receiver which describes the relationship between the contact force F_c and a target quantity x . Thus,

$$x'_c = H_r F'_c \quad (\text{A.7})$$

The target quantity x'_c (which may be a sound pressure or velocity for example) is the response at a point of interest when the source is operational whilst coupled to the receiver. H_r is a measure of the receiver whilst it is uncoupled from the source, hence the subscript r .

Another quantity of interest is the complex power Q ,

$$Q = \frac{1}{2} F_c^* v_c = \frac{1}{2} \frac{|v'_{sf}|^2}{|Y_s + Y_r|^2} Y_r \quad (\text{A.8})$$

In particular the real part of the complex power is of interest (which is referred to as the active power) as this stands for a net energy flow from the contact point out to the receiver. Thus, only the active part of the power results in a response at the point of interest, i.e. where the target quantity x is defined. It is important to note that the active power Q , the contact force F_c and the contact velocity v_c are all dependent on the properties of both the source and receiver structures.

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