DESIGN ISSUES FOR MICRO-GENERATION EQUIPMENT INSTALLED IN HOUSES

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1 INTRODUCTION

Whilst fridges, washing machines and conventional domestic heating systems are well accepted and generally well refined products, the introduction of energy generating equipment such as combined heat and power units (CHP), micro-windturbines and heat pumping systems into a home can be a potential source of nuisance to both the home-owner and any attached neighbours. This paper outlines some of the issues involved in installing machinery in a low noise domestic environment, particularly those related to structure-borne noise, highlighting some of the steps that need to be considered to ensure a successful installation.

The sound power of sources of airborne noise is relatively easy to measure, and domestic appliances are generally labelled with an overall A-weighted level. For sources of structure borne noise however, the situation is very different. For example the introduction to standard EN12345-5, reference [1], states that: "The estimation of sound levels due to service equipment in buildings is a complex task and structure borne noise sources and transmission are not completely understood". Although this standard provides methods for estimating structure borne noise, the calculations are complex for an acoustician, let alone a boiler installation engineer.

An additional issue is that the construction and the acoustic environment in a "green building" can be different to conventional buildings in a number of significant ways:

- Double or triple glazed windows substantially reduce levels of interior background noise, which will tend to make any internal sources of noise more noticeable.
- Energy efficient construction can often mean lightweight internal walls, which makes the building more susceptible to structure-borne transmission.
- Machinery installed in a green building may be very different to normal domestic appliances

Examples of these issues can be found in Hodgson [2], which points out that the acoustical aspect of the green office buildings surveyed was judged by the occupants to be the least satisfactory aspect of the buildings.

For commercial buildings the design work will generally involve proper acoustic calculations so there is the potential to get things right at that stage. For domestic houses, however, the scope for detailed design calculations is very limited, even more so with retrofit. Instead the success of any installation is dependent upon the quality of advice from the equipment manufacturer and the experience of the installer.

2 THE STRUCTURE BORNE NOISE PROBLEM

2.1 Structure-borne power

As already noted, it is relatively easy to quantify the airborne sound power of an appliance and to calculate the impact of this on the local noise level; the sound power is reasonably independent of location, the main impact is generally confined to one room and calculating the effect of airborne noise in other rooms is also straightforward. This contrasts with the structure borne sound power of the appliance, where the vibrational power injected into the building can vary greatly between different installations, the dominant impact is likely to be in more distant rooms and calculating propagation over long distances through a building can be quite inaccurate. This is illustrated in figure 1, where for room A the airborne noise will dominate but in room B it is likely that structure borne noise will be dominant.

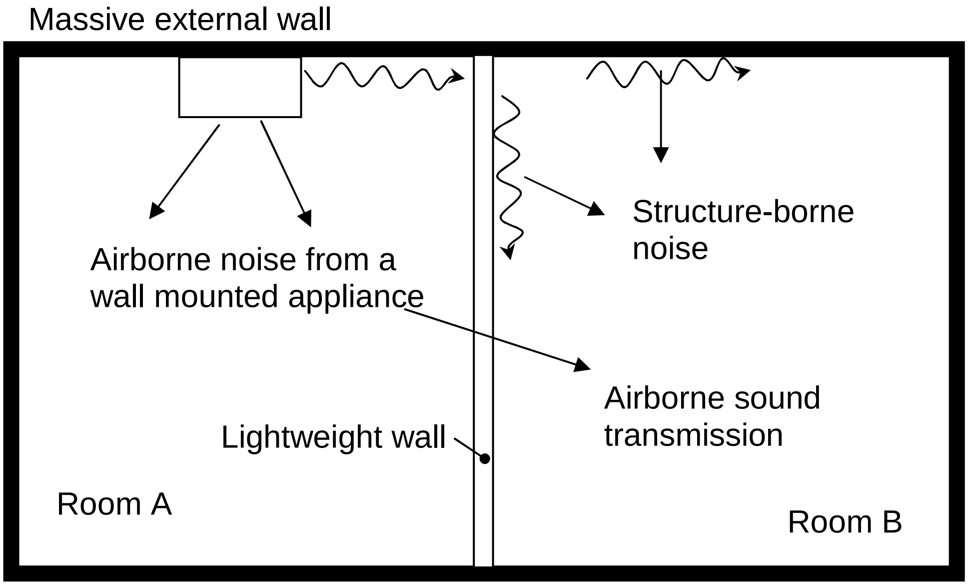

Figure 1 Schematic of the structure borne noise problem

This diagram highlights a number of other issues. Firstly the appliance here is attached to an external wall, which is assumed to be reasonably massive, but the noise radiation into room B might well be dominated by the relatively lightweight wall between the rooms acting as a sounding board. This may make it difficult to distinguish between airborne noise from room A and structure-borne sound radiation from the partition.

The power injected into the wall depends on the relative impedances of the wall and the appliance, but a device that is firmly fixed to the wall is likely to act as a force source, and the power is given by

$$P = 0.5|F|^2 \operatorname{Re}(M) \tag{1}$$

where F is the applied force and M is the mobility of the wall. For a large wall at high frequencies the mobility may be calculated approximately from the bending stiffness, B_p , and surface density of the wall, m_0 , to give

$$P = \frac{|F|^2}{16\sqrt{B_p m_0}} \tag{2}$$

From this equation a second issue may be noted: the situation would be far worse if the appliance were attached to the partition. In that case both stiffness and surface density would be much lower than for the external wall, resulting in more power flow and more structure borne noise radiation. A common example of this mistake is that hand driers in public toilets are too often fixed to a stud wall, thus making them substantially noisier than they need to be.

A third important issue however, is that even if the appliance is fixed to the external wall, it is still difficult to estimate the power flow because of the uncertainty in the mobility. Figure 2 shows the point mobility of a typical wall or floor slab, from which it is apparent that mobility could vary by a factor of 10 – 100 over a wide frequency range, so that power, and hence noise, may vary by ± 5 – 10dB relative to a mean power based on equation (2) for a single frequency excitation, depending on whether the wall is at a resonance or an anti-resonance.

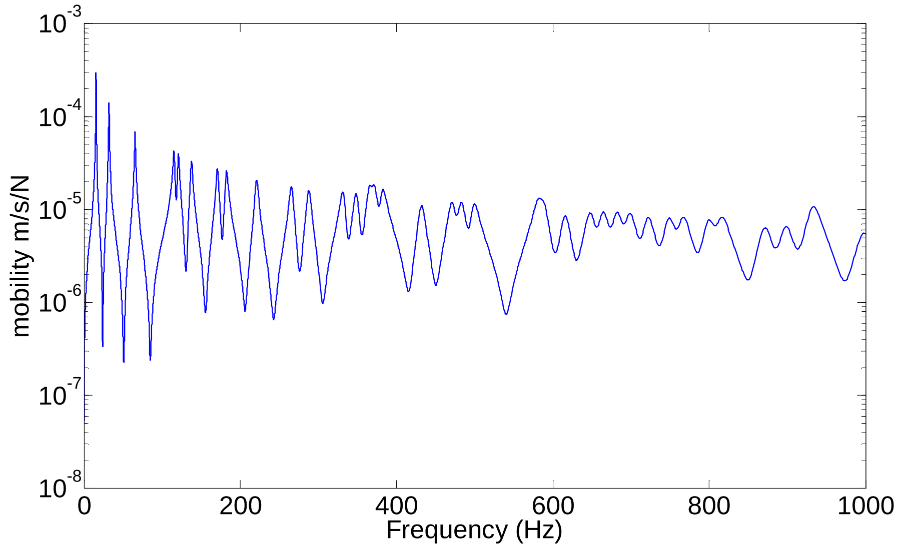

Figure 2 Point mobility of a 2.5 x 6.3 x 0.1m simply supported concrete slab assuming an excitation point at the middle of the wall and 2% damping.

Whilst many appliances produce relatively broadband excitation, so that variation in the level of individual frequencies has little impact on the overall level, some devices such as pumps or CHP boilers may have a few dominant excitation frequencies and it may be expected that the structure-borne noise from these appliances will be far more installation dependant.

2.2 Measurement of structure borne power

Given the inherent installation dependence of structure-borne sound sources, it is clearly difficult to develop a suitable standard for measuring it.

One existing standard relates to equipment for the water supply industry, ISO 3822 [3], where a water pipe is connected to a wall, and noise radiation from the wall is measured. There is no direct measure of the power produced by the test item, instead a comparison is made with a reference source of noise in the water pipe, an orifice, and the noise of the test item is ranked relative to that. Whilst this does provide useful information to the industry, a recent publication suggests that some of the assumptions in this standard do not apply [4] and that that this leads to problems in rank-ordering appliances.

The method of ISO3822 is superficially similar to the reception plate method described in reference [5] although the latter does provide a measurement of the power flowing into the receiver plate. One conclusion to note, however, is that “It remains to be considered how the reception plate power, obtained with the machine under test in the laboratory, can be transformed to yield the installed power from the same machine in a building”. The answer to this problem lies either in a suitable scaling law for the mobility of the building compared with the reception plate, or possibly in the concept of characteristic power introduced by Moorhouse [6].

A final method of characterising machinery is through ISO9611 [7], which specifies the measurement of velocity of contact points of isolated machinery. Combining the velocity data with information about the stiffness of the isolators can be used to infer a first order estimate of the forces at the mounting points.

2.3 Prediction methods for noise

The power flowing into the building structure is mainly a nuisance because of the re-radiated noise, and so it is useful to extend the power flow modelling to consider that aspect. For radiation from the main wall the radiated sound power is given from

$$W_{rad} = \rho_o c\sigma\, S \left\langle v^2 \right\rangle \tag{3}$$

Where $\rho_0 c$ is the characteristic impedance of air, σ is the radiation efficiency of the wall, S is surface area and $\left\langle v^2 \right\rangle$ is the space averaged mean square velocity. The energy balance equation for the plate gives that

$$P = \omega\, m_o S \left\langle v^2 \right\rangle \eta \tag{4}$$

and so

$$\left\langle v^2 \right\rangle = \frac{P}{m_0 \omega \eta S} \tag{5}$$

It is clear that increasing the mass of the wall, whilst keeping stiffness constant, reduces radiated sound power both indirectly by reducing the mechanical power input through equation (2), and directly by reducing the mean square velocity through equation (5). An additional small benefit is that radiation efficiency may be reduced at low frequencies as adding mass tends to increase the coincidence frequency.

Predictions where there is more than one wall, as in figure 1, require more sophisticated models such as finite element analysis (FEA) at low frequencies or statistical energy analysis (SEA) at higher frequencies. The prediction model of EN12354 uses what is essentially a simplified SEA model, with examples of its application being found in references [8] and [9], both papers showing reasonable agreement with measured data.

3 ADVICE FROM MANUFACTURERS AND OTHER SOURCES

During the course of writing this paper various manufacturers were approached for information on the guidance given to installation engineers. Given the difficulties outlined above, it is perhaps unsurprising that although everyone contacted was helpful, there was a general lack of specific detail on what the levels of structure-borne noise were likely to be and how this compared with the airborne sound power for the same machine.

Published comparisons of airborne and structure borne sound power are rare, although reference [6] does this for a centrifugal fan for which structure borne power tended to dominate at low frequencies and vice-versa at high frequencies. It should be noted though that not all of this structure-borne power is radiated as noise.

Some information comparing heatpumps with other appliances, such as refrigerators, is available on the Worcester Bosch web site, although it seems that none of this data relates to structure-borne noise.

The Baxi-ecogen boiler is a Stirling engine based micro-CHP unit that is designed to be a direct replacement of a conventional boiler, and according to the manufacturer there are only limited constraints on installation location. The main requirement is that the boiler should be installed on ‘a suitable load-bearing wall’, although installation in a bedroom should be avoided.

The WhisperGen micro-CHP boiler also uses a Stirling engine, but in this case it is not designed to replace the conventional wall mounted boiler. Noise is noted as an issue in the manufacturers advice on locating the unit, suggesting that sensitive areas such as kitchens and bedrooms should be avoided. The advice also points out both the need to avoid contact with stud partitions and that anything other than a solid concrete base should be 'acoustically isolated from the rest of the building'.

Information was also sought for results of a recent UK Government funded study on micro-wind turbines but this is not yet in the public domain.

4 METHODS FOR LIMITING STRUCTURE BORNE NOISE

The first step in ensuring that structure-borne noise is not a problem is to ensure that the appliance is installed on a surface that is sufficiently high impedance relative to its mass. This is a function of both the global properties of the wall and the location of the installation, with supported edges being relatively less mobile than a mid-span location. One example of this is that the main engines of a ship will always be mounted on stiff foundations, probably with additional local stiffening and added mass; whilst the stiffening is mainly done for structural reasons there are also clear benefits for noise and vibration and the same approach will work in a house.

The next step in reducing structure-borne noise is to install vibration isolation, with the effectiveness of any treatment being a function of the mobilities of the source, Y_S, the receiver structure, Y_R, and the isolator Y_I. The effectiveness of the isolator, given from equation (3) [10], is a function of the impedances of the resonant frequency of the isolator, and figure 4 shows an example of installing an idealised 5Hz isolator for an appliance fixed to the wall whose mobility is plotted in figure 2. The isolator provides a clear benefit, overestimated here at audio frequencies because it neglects many limiting factors, but the issue of resonances in the receiver structure is clearly still a potential problem.

$$E_I = \left| 1 + \frac{Y_I}{Y_S + Y_R} \right| \tag{3}$$

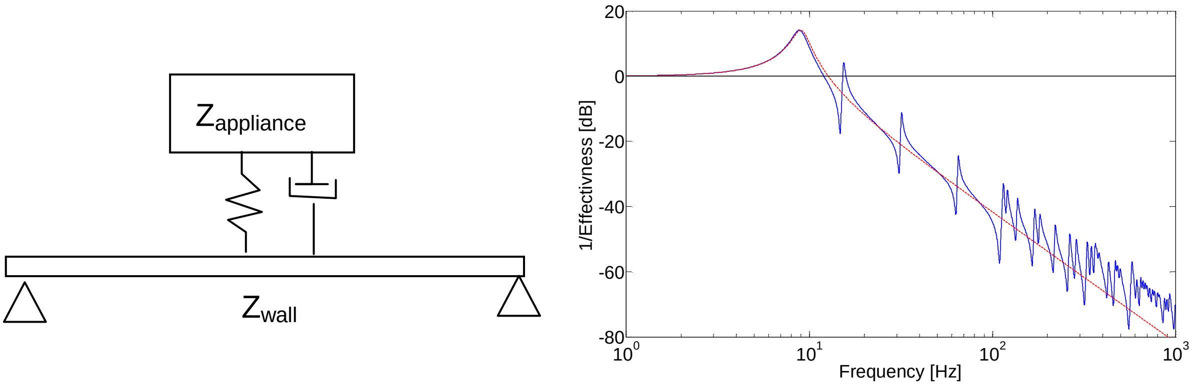

Figure 3 Effectiveness of a 5Hz isolator for a 120Kg mass on the wall specified in figure 2, showing results for a finite plate (blue) and an infinite plate(red dotted)

However, the biggest problem with isolators is that they are unsuitable for many products where a stable fixing is required, gas boilers being one example. In that case the best option for resolving a noise problem caused by a resonance is to retune the system in some way:

- since the mass of the appliance will modify with resonant frequencies of the wall, a change in the position of the appliance may shift an undesirable resonant frequency.
- dynamic absorbers and secondary masses can shift or split a resonance
- the structure could be stiffened locally.

- Equation (5) indicates that damping will reduce noise. Increasing the damping of structural walls is difficult, but for stud walls multi-layered plasterboard has significantly higher damping than a single layer.

5 CONCLUSIONS

Unlike airborne sound power, there is insufficient data available for the structure-borne noise of domestic power generation and heat pumping machinery to be assessed accurately, and some caution is recommended to avoid expensive noise problems:

- Appliances should ideally be installed on floor slabs, though installation on structural walls may be acceptable for appropriate equipment.
- Installation on stud walls and timber floors or ceilings should be avoided.
- The low background noise levels in well insulated buildings is an issue, so that there should always be sufficient distance from source to noise sensitive locations (including neighbours)
- It is generally accepted that structure-borne noise follows the shortest route, so consideration of all flanking paths is important.
- Lightweight walls anywhere along the transmission path may act as a sounding board, though these can be damped. Double glazing can also act as a sounding board, especially at the mass-air-mass resonant frequency of typically 150-230Hz; windows will also act as a band pass filter for external airborne noise at the same frequency.
- Vibration isolation should be installed where possible.
- If problems do occur despite following the advice above, then this is likely to be due a resonance condition and the system can be retuned by adding mass or stiffness to the support structure.

6 REFERENCES

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