Prediction methodologies for vibration and structure borne noise

Malcolm Smith[a]

(a)   ISVR Consulting, University of Southampton, UK. mgs@isvr.soton.ac.uk

Abstract

The need to meet design limits on noise and vibration for machinery installed in any structure, whether buildings, ships or spacecraft, means that there is a requirement for reliable prediction methods to optimise engineering designs. Many diverse noise and vibration criteria could apply, ranging from limits for noise at work or in living areas, through to limits on vibration for human comfort or to protect sensitive equipment.

Predictions close to the source are generally fairly straightforward, using airborne sound transmission methods for noise or simple dynamic models for vibration. At larger distances however, where there may be multiple transmission paths for both vibration and structure borne noise, more sophisticated prediction methods are generally required.

This paper reviews some of the techniques that could be useful for predicting vibration and structure borne noise in a range of situations, highlighting issues that need to be considered in each case, such as how extensive and detailed does the model need to be, how are inputs from the machine specified and what are the effect of energy losses.

Introduction

It is relatively easy to measure the acoustic sound power of a machine and to calculate local noise levels; the sound power is reasonably independent of location, the main impact is generally confined to one room and calculating the effect of airborne noise transmitted to other rooms is also straightforward. This contrasts with the vibrational power the same machine injects into the support structure (i.e. building, ship, rig, car, train, aircraft, spacecraft, etc.) which can vary greatly between different installations. Indeed, the introduction to the European standard on estimating structure-borne noise in buildings, EN12345-5 (2009), 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 rather complex and difficult to apply.

The main impact of structure borne noise is likely to be in more distant spaces, as illustrated in figure 1 for the case of a building with an appliance fitted to the wall. For room A the airborne noise will dominate, in room B there will be contributions from both the airborne and structure borne noise, but in room C it is likely that structure borne noise will be completely dominant.

This example also 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 rooms B and C might well be dominated by the relatively lightweight walls between the rooms acting as sounding boards. In room B this may make it difficult to distinguish between airborne noise from room A and structure-borne sound radiation from the partition, except by measuring its transmission loss and level of vibration level. Secondly, the structure power radiated into rooms B and C is a function of the losses along the transmission path; this is affected by material damping, but losses are also increased by fixtures and fittings and by energy flowing into any other attached building structure.
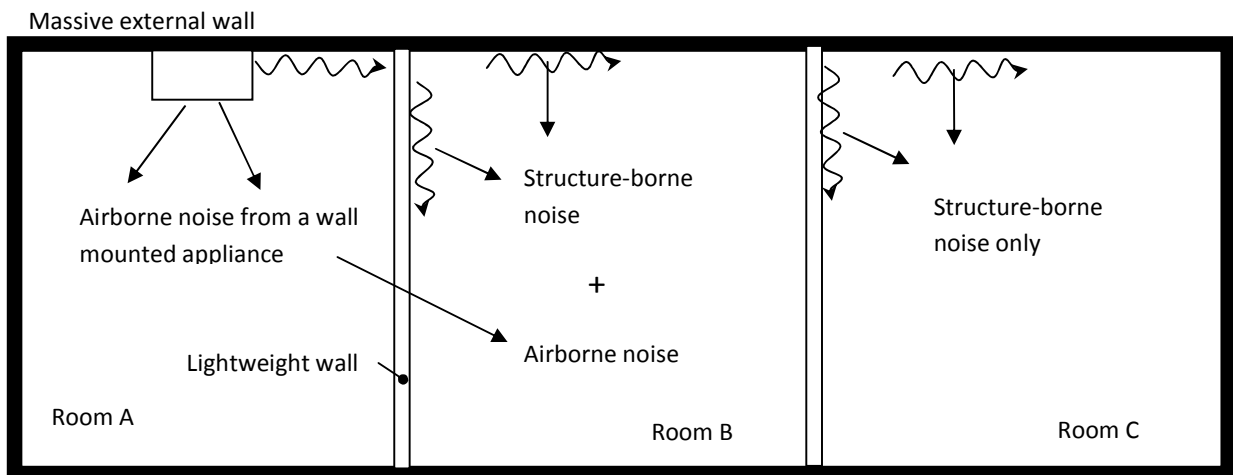

Figure 1 Schematic of the structure borne noise problem for a building

The vibrational power injected into the structure depends on the relative impedances of the wall and the appliance, as described by Moorhouse (2001) and Gardonio and Brennan (2006), but a device that is firmly fixed to a massive structural wall is likely to act as a force source for which the power is given by:

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

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

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

From this equation another 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 (though it should be noted that the force source model may no longer be valid). A common example of this mistake is that hand driers and ventilation fans are too often fixed to a stud wall, thus making them substantially noisier than they need to be.

Whilst such simple models of power flow into an infinite structure are useful, any real structure has resonances so that the mobility is strongly dependant on frequency. Figure 2 shows the point mobility of a typical wall or floor slab of a building compared with the infinite structure mobility used in equation 2, 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 ± 5–10 dB 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.
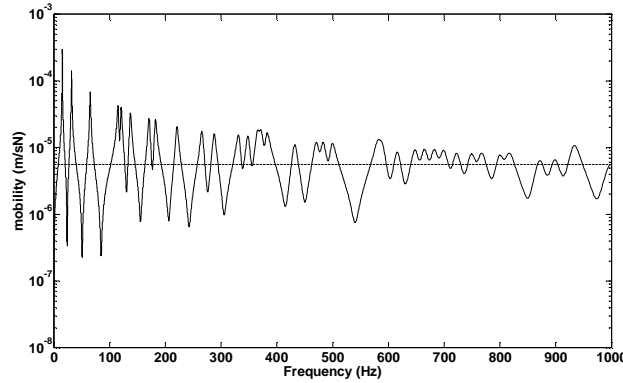

Figure 2 Point mobility of a 2.5 x 6.3 x 0.1m simply supported concrete slab assuming an excitation point at the centre and 2% damping. Solid line = finite structure; dotted line = infinite structure

Whilst some devices produce broadband excitation for which the variation in level at individual frequencies has little overall impact, most are machines have reciprocating or rotating components which produce discrete frequency vibration, and the variation in power input can be considerable depending on how these match the resonant frequencies of the structure and how the motion of the machine couples to the modes of the structure. Whilst the response at any specific frequency depends on whether the wall is at resonance or not, the frequency average vibration level may be estimated using the energy balance equation from Statistical Energy Analysis (SEA), Lyon and de Jong (1995):

$$P = \omega \, m_o S \left\langle v^2 \right\rangle \eta \qquad (3)$$

Here, the power input from the machine, P, is equated to the power losses in the plate due to damping which are given from the space averaged mean square velocity, $\left\langle v^2 \right\rangle$, the damping loss factor, η, and the surface area , S. The space and frequency average mean square velocity is thus given as:

$$\left\langle v^2 \right\rangle = \frac{P}{m_0 \omega \eta S} \qquad (4)$$

and the radiated acoustic sound power, W_{rad}, may be calculated from:

$$W_{rad} = \rho_o c \sigma \, S \left\langle v^2 \right\rangle \qquad (5)$$

Where $\rho_0 c$ is the characteristic impedance of air and σ is the radiation efficiency of the wall, Fahy (2007).

Equations 1 – 5 provide an initial means of estimating the level of vibration and structure borne noise that will result when a machine is attached to a plate-like structure, although it only does this for the simplest possible case of a point force applied orthogonally to the plate, and only predicts a space average and frequency average response.

Much of the remainder of this paper discusses how to deal with some of the factors that must be considered in estimating the response of real structures due to the installation of real machines. First however, any prediction method must be suitable for purpose and so it is useful to categorise the criteria that need to be met in various situations.

Assessment Criteria and limits

Noise and vibration criteria may be broadly split into three main categories: noise limits for human comfort or safety, vibration limits for human comfort or safety and vibration limits to ensure integrity or operational stability of the machinery and structure. Noise limits for machine integrity reasons do exist but are relatively uncommon.

Dealing first with human noise exposure criteria the WHO (1999) guidelines indicate A-weighted levels in the range 30dB(A) for comfort up to 85dB(A) or higher for health and safety. Similar noise limits are incorporated into national noise at work regulations, and international regulations such as IMO A.468 (1982) for the marine industry. The A-weighting means that means that these criteria generally affect frequencies above 100Hz.

With respect to human exposure to vibration, limits for comfort and health and safety purposes are set out in ISO2631 (2001) and ISO6954 (2000). These criteria generally set limits on velocity or acceleration levels, for which frequencies below 100Hz are generally most important.

The final category, vibration limits for machine integrity, may be machine specific (e.g. vibration limits to ensure data transfer efficiency in computer disk drives), but there are also a number of general guidelines and limits for various cases. Examples include the limits on machinery vibration given in ISO 10816 (2009) and the criteria for vibration sensitive equipment proposed by Gordon (1991).

Prediction methodologies

Classifying problems as low frequency or high frequency matches the similar division of prediction methods, depending principally on the modal density of the structure at the main frequencies of interest. For high frequency / high modal density problems the most common approach is Statistical Energy Analysis (SEA), whereas for low frequency / low modal density problems Finite Element Analysis (FEA) is used; hybrid FEA-SEA models are now also available which attempt to avoid the frequency limitations of the individual methods, see for example Cotoni and Shorter (2007).

Both FEA and SEA are well established techniques for which commercial software packages are available, and the next section provides a couple of typical applications. However, it is also useful to consider empirical and semi-empirical methods as described in the third example.

The key to any absolute prediction is a good characterisation of the source, but given the installation dependence of sources of vibration it is clearly difficult to develop a suitable standard for measuring them. One easily applied standard is ISO9611 (1996), which specifies the measurement of velocity at contact points of machinery installed on isolators. This velocity data can potentially be combined with information about the stiffness of the isolators to infer a first order estimate of the forces at the mounting points, or alternatively an FE model can be used to determine what forces would give rise to this level of vibration. This is the method used in example 1 below.

Where the only measurements possible are on hard mounted machines, it is necessary to resort to either a more detailed measurement exercise to characterise the receiving structure with the machine installed, see for example Pinnington (1990) or Moorhouse (2009), or using an FE model of the reference structure to scale the response to the new structure.

For energy flow models such as SEA the normal approach is to measure space averaged vibration levels on the source subsystem, and to infer the power input using equation 3. This method was used in the study described in example 2, and is essentially the same as the reception plate method described by Spah and Gibbs (2009). The extension of this to structures with multiple power inputs is carried out using experimental SEA, which is often used to provide source breakdowns for motor cars in particular.

Case studies

Example 1: application of FEA to low frequency vibration transmission through a building

This class of problem is very common, with examples including transmission of engine vibration in ships and oil rigs or response of buildings to underground railways. The example shown in figure 3a) is to ensure that vibration inside the building is below the VC-A vibration criterion for sensitive equipment given by Gordon (1991) when a generator set on the roof of the building is operating.

In outline, the steps in the modelling process are:

- Build an FE model of the building with the machine on isolators; the generator is modelled as rigid body and raft with the correct masses and moments of inertia and mount stiffnesses, and unit forces are applied to excite all modes of vibration (vertical, lateral, rocking, etc.).

- Predict the response of the generator; calculate RMS response over all mounts and directions; also predict the response at locations throughout the building as required.

- Measure vibration on a generator mounted on isolators at another location in accordance with ISO9611; calculated RMS response over all mounts and directions.

- Use the measured source data to scale the FE predictions.

The model of the machine on isolators provides an estimate of the effective forces that must be acting, and the model gives a prediction of the resulting building vibration, figure 3b). The same forces may then be used to model the response that would be seen without the isolators; in this case the VC-A criterion would be exceeded.
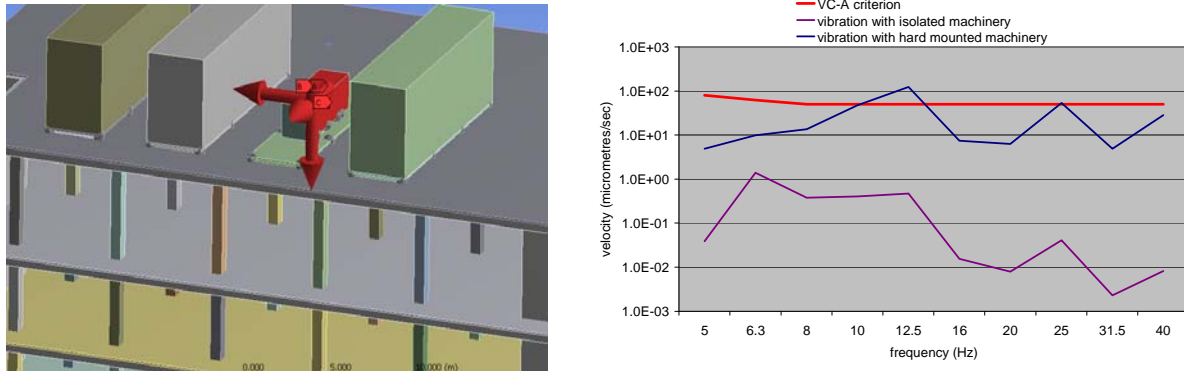

Figure 3 a) FE model of a building with generators on the roof b) vibration response at a location inside the building with and without isolators installed compared with the VC-A criterion from Gordon (1991)

Whilst this method is reasonably straightforward there are many hidden assumptions and approximations. Important amongst these is the fact that the linear forces and torques applied by the machine have not been explicitly resolved, which increases the uncertainty in the predictions. Another consideration is the level of damping used in the model; the damping needs to take account of losses for a fully fitted building, and also the effect of attached building structure or radiation damping into the ground for machines in the basement.

Example 2: application of SEA to predict structure borne noise in a ship

Ships and oil rigs have particular issues with structure borne noise because these steel structures are very efficient at transmitting vibrational energy, there are many sources of vibration and there are likely to be tight limits on noise levels in crew living quarters. An example is shown in figure 4,

The issues to be considered in setting up an SEA model for this type of problem are:

- Decide how extensive the model needs to be. Although direct paths are likely to dominate the energy transmission for a bare vessel, once this path is treated the secondary flanking paths will be very important and need to be included. Additional structure and radiation into the water act as a sink of energy and need to be included.

- Characterising the source powers for the various items of machinery is a key aspect of an SEA model. This could be done using either the reception plate method, i.e. measuring space average vibration levels on another installation and specifying this as a source subsystem energy level in the model. Some care is needed with this approach since the power input does not necessarily change in the correct way as the structure is altered; for example if damping of the source s

- The level of trim in the vessel will not only affect the sound transmission characteristic between acoustic spaces, but will also affect the level of structural damping.

- The most effective use of SEA is for 'scaling' from one structure to another, and this is inherent in the definition of source subsystem energies described here, but FEA models can play an important part in modelling the sources of vibrational power.
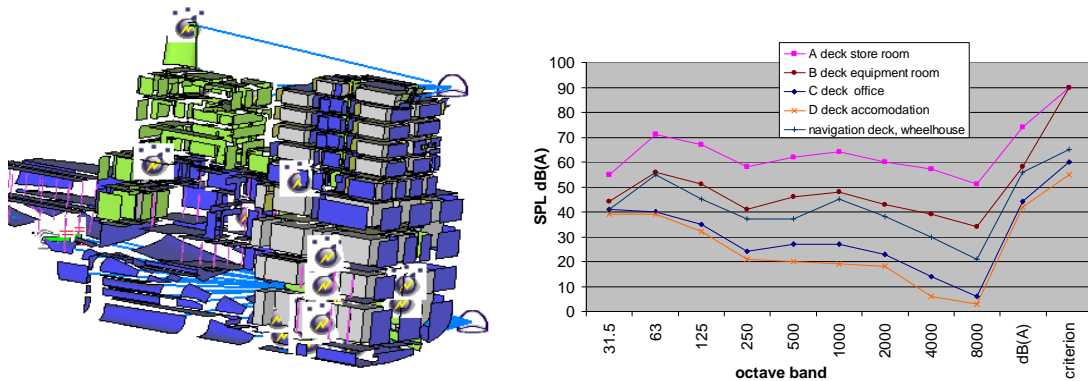
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Figure 4 a) SEA model of a ship, showing an exploded view of the structural and acoustic subsystems and the machinery sources b) predicted noise levels at typical locations.

Example 3: application of semi-empirical methods to ground borne vibration from a train

New metro lines have to be designed with track isolation systems to ensure that they do not cause unacceptable levels of ground borne noise and vibration in buildings above the line. Besides the cost of installing and maintaining these systems, there may be adverse effects on train stability and hence speed. There is thus always a need to ensure that any system is optimised for both rolling stock performance and acoustic performance.

For new sites it is probably necessary to resort to numerical prediction methods, but for sites where there may be changes of rolling stock or track formation, or new buildings are being constructed, it is often better to use measured source and transfer function data. How this is done depends on particular circumstances and this methodology outlines some possibilities:

- The train has to be characterised as a source of vibration, the starting point being a measurement of vibration measurement during a train pass-by. However, the train comprises a line of axle sources, with the contribution of each axle depending on distance from the measurement point. Measuring vibration on the tunnel wall has some advantages over measurements on the track to avoid near-field effects.

- Measure transfer functions from a force input on the track (using an instrumented hammer) to vibration on the wall and vibration on the ground surface. For the latter measurement it may be beneficial to measure the reciprocal transfer function to exploit the lower level background

vibration in the tunnel. Transfer functions for a set of points down the length of a train are required so that the response at the surface can be calculated for the line of axles.

- Use an empirical model of transmission into the building to predict the ground borne noise level inside. For example Thompson (2009) outlines the use of the 'Kurzweil' formula $L_p = L_v - 27$, where L_p is the sound pressure level re 20 μPa and L_v is the velocity level in dB re 10^{-9} m/s.

- Modelling the distribution of energy through the building could use similar empirical methods, for example the correction factors for attenuation / floor set out in Nelson (1987), or could use FEA or SEA methods depending on the frequency range.
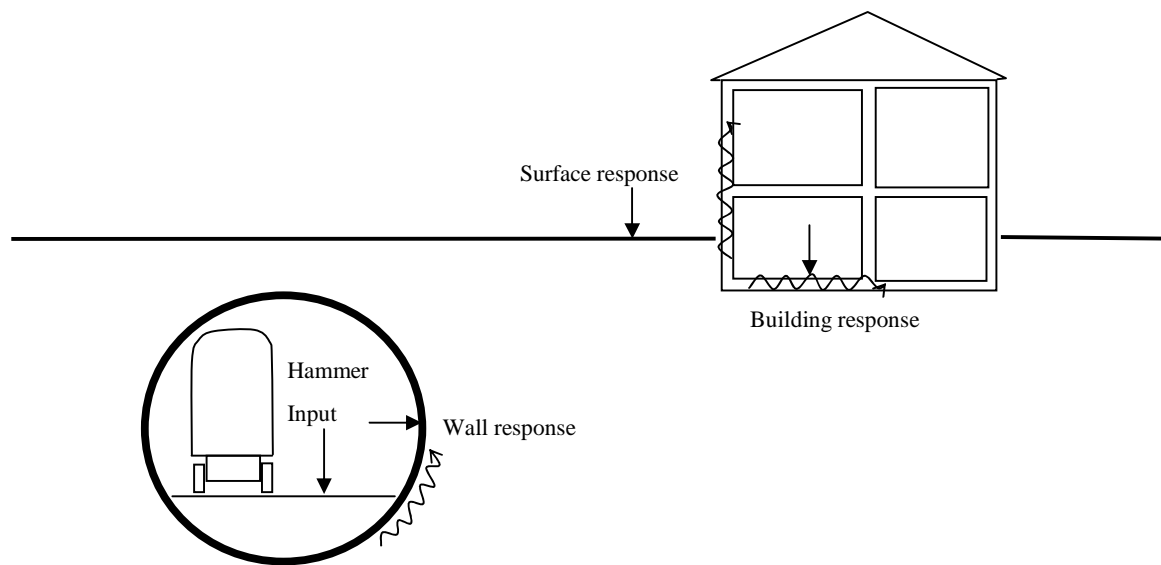

Surface response

Building response

Hammer
Input

Wall response

Figure 4 Illustration of measuring of source vibration levels and transfer functions from a bored tunnel to the surface and into a building

Conclusion

The aim of this paper has been to highlight some of the combinations and permutations of methods that are possible for predicting transmission of vibration and structure borne noise in a range of practical situations. Whilst in has been necessary to skim the surface of each method, the main message is that understanding the basic physics of the transmission process is always important: what is the source of vibration and what are its spatial and frequency characteristics; how does the source couple to the structure and what is the resultant power input; how does the energy spread out from the source, and what controls losses along the transmission path; what is the assessment criterion and is the prediction method fit for purpose.

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