MY THUMB IS ON THE BICYCLE PUMP – CONSIDERATIONS FOR THE VENTING OF AIR CAVITIES BELOW STRUCTURALLY ISOLATED FLOATING FLOORS

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1 INTRODUCTION

Performance spaces and fitness developments are commonly designed with floating floors to attenuate the low frequency sound fields which their activities generate. Whilst the natural frequency of the primary structure, floating element and isolation bearings are of critical importance, it is possible that the air trapped below the floating floor can become stiffened by the deflection of the floor, reducing the insertion loss of the system.

This paper summarises the issue and proposes a process by which the impact of this phenomenon can be assessed, which involves calculating whether there is sufficient time for stiffening effects to occur, assessing whether connected volumes can accommodate air movement, and using volume flowrate to size a “vent opening” in the system if previous steps suggest this is necessary.

It is noted that providing a precise analytical model of the behaviour of semi-pressurised air below a slab is complex and requires a number of assumptions. As such this paper attempts to provide a conceptual framework to consider the physics of the phenomenon and to strengthen the judgements that engineers must make regarding venting the cavity.

2 SCENARIO – FLOATING FLOORS

2.1 Background

In developments which include both activities which generate significant levels of low frequency sound energy, ***and*** room usages which are sensitive to noise ingress it is common to structurally isolate the source (and sometimes receiver) of this low frequency energy with a ‘box-in-box’ solution, where a structurally isolated “inner box” sits within the “outer box” of the primary structure.

This strategy is common in acoustics engineering, and is typically seen in performance space developments (where musical instruments or amplification equipment can generate very high levels of low frequency airborne sound) or fitness developments (where activities with high dynamic live loads such as people jumping, or dropping of weighted implements) introduces energy into the slab which is manifested as low-frequency structure-borne noise.

The image below illustrates the basic concepts.

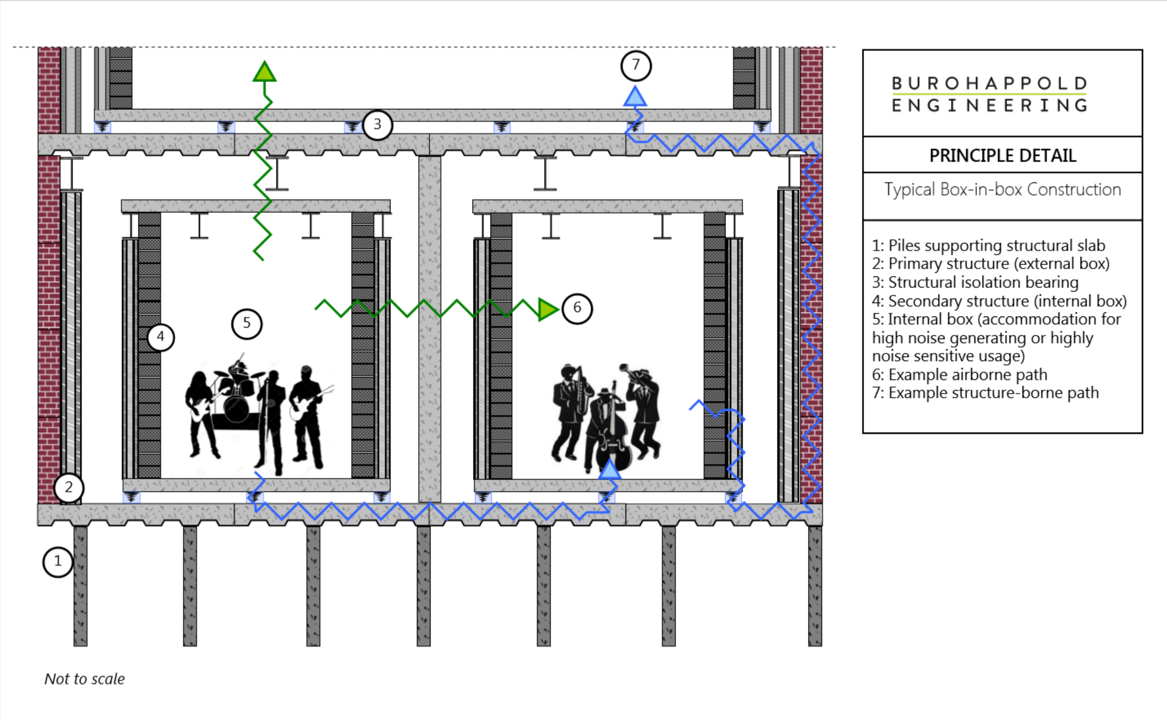

Figure 2-1 Box-in-box design: concept

Higher frequency sound energy (typically >250 Hz) rarely has the energy necessary to strongly excite structural elements as the energy of an acoustic wave is proportional to the square of its amplitude. Therefore, when sound is transmitted by structure-borne pathways, the higher frequencies are rarely of primary concern. These phenomena are contrasted with the lower frequencies (typically <250 Hz) which tend to 'flank' between adjacent spaces via connected structural elements.

To prevent this flanking phenomenon, structural breaks are often implemented, with the most efficient type being a simple air gap (across which vibration cannot easily be transmitted), although resilient methods are also possible. Whilst an air gap is usually simple to accommodate between the "sides" and "lids" of the boxes, gravity dictates that the "base" of the box must be supported somehow (unless the box is hung from its walls which is unusual due to its problematic engineering).

A 'floating floor' in the context of this paper is therefore taken to mean a secondary floor slab which is isolated from primary supporting structure via resilient means and forms the "base" of a structurally-isolated box-in-box solution.

An example of this is highlighted in the following image.

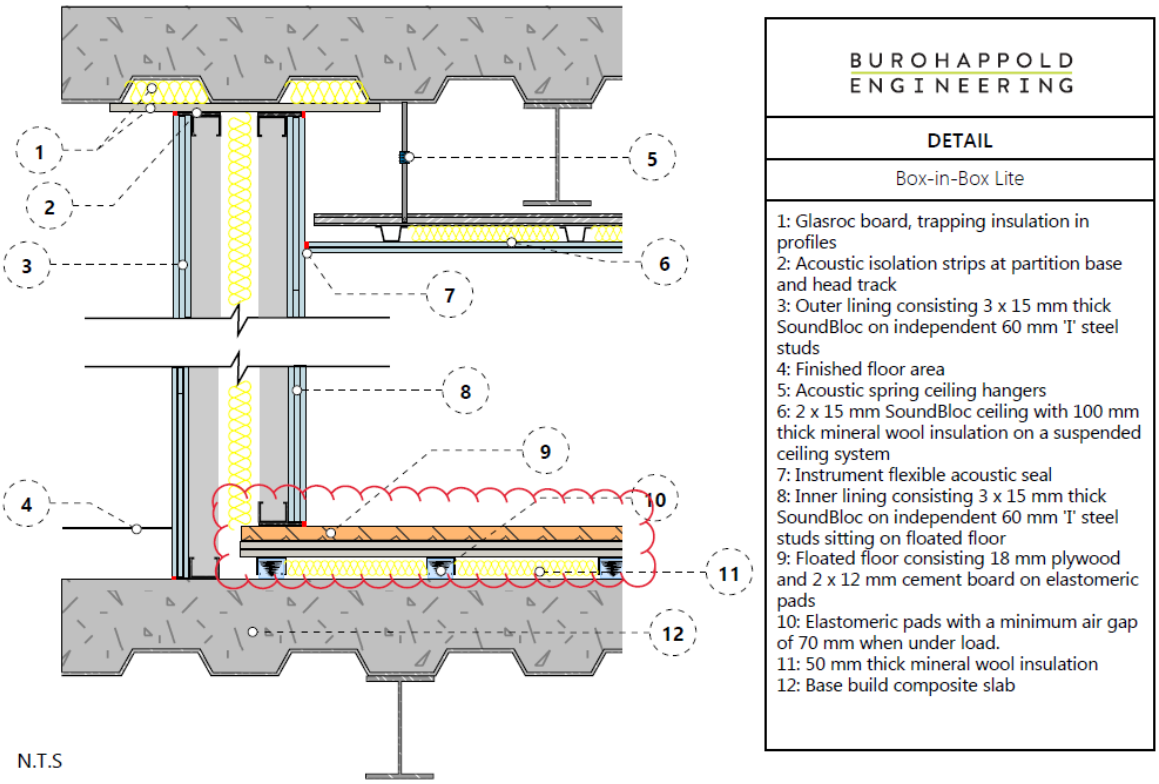

Figure 2-2 Floating floor - example

2.1.1 Performance

In order for a floating floor to provide efficient insertion loss, it is necessary for the resilient elements supporting the floating slab to be the most compliant part of the system. Both elastomeric and steel spring bearings are common, with manufacturers typically able to achieve a lowest natural frequency of approximately 6 Hz for elastomeric bearings, and 3 Hz for steel springs.

The selection of appropriate bearings is contingent on the fundamental frequency (Fn) of the primary structure, with higher Fn being preferable both in terms of efficiency of isolation (less deflection in the primary structure means that the system behaves more closely to single-degree-of-freedom model with the isolating deflection being done by the bearing or spring and in terms of unlocking less challenging bearing solutions.

If the Fn of the primary structure is low (for example, Fn = 5 Hz), this suggests that a steel spring isolator with an Fn of perhaps 3-4 Hz is the appropriate solution (there is an idealised rule for frequency ratios which is the square root of 2). However, the spring solution is typically more costly than an elastomeric equivalent and the low Fn required introduces significant Z-axis deflection (between 28 and 16mm of static deflection, for 3 and 4 Hz bearings respectively) which must be accommodate elsewhere in the design (e.g. at door thresholds, ceiling/wall junctions and in any penetrating service pipes or ducts).

It is also critical that the actual floating slab is considerably stiffer than the bearings themselves, such that the bearings amount to a highly compressible "filling" in a slab "sandwich" with the slab appearing as if a limp mass. Ideally the Fn of the floating slab would be at least 2x the Fn of the primary structural slab, however as a minimum $\sqrt{2}$x the Fn of the primary structural slab is required.

2.1.2 Trapped Air

When the floating slab experiences Z-axis deflection, the pocket of air trapped underneath undergoes a degree of compression. A helpful analogy is to consider placing a thumb over the air supply hole of a bicycle pump. In this example, the user might be able to reduce the volume of the pump barrel by perhaps 50% when pushing in the handle. This is a tangible example that air is compressible – but not infinitely so.

In the context of the floating slab, it is important to consider the Fn of the air pocket when compressed by the Z-axis deflection of the slab. If the Fn of the air pocket (under compression) is greater than that of the bearings, then the higher Fn dictates the level of insertion loss provided as the two stiffnesses add in parallel.

However, if the perimeter of the air gap at the edge of the floating slab is not sealed, it is possible that the full air stiffening effect won't apply as some of the the trapped air forming the pocket has sufficient time to "escape" from the void under the slab The typical approximate rule is that spatial effects for wave phenomena become important when the size of the field becomes comparable in size with a quarter wavelength of the wave. It is important to note that this approximate relationship relies on the speed of the acoustic wave under the floor and not the transportation speed of the air itself. The mental model of this phenomenon is that a small area floor that is leaky at the perimeter will not trap air efficiently, but a very large area floor will. The quarter wave approximation gives a rational basis to define what counts as a large area floor – i.e. it is large when compared with the acoustic wavelength in the air gap.

In the simplified example below, if the slab is at rest at Position 1, then its oscillation generates peak negative amplitude at Position 2. The distance between these points represents the period during which any trapped air is becoming compressed and stiffened.

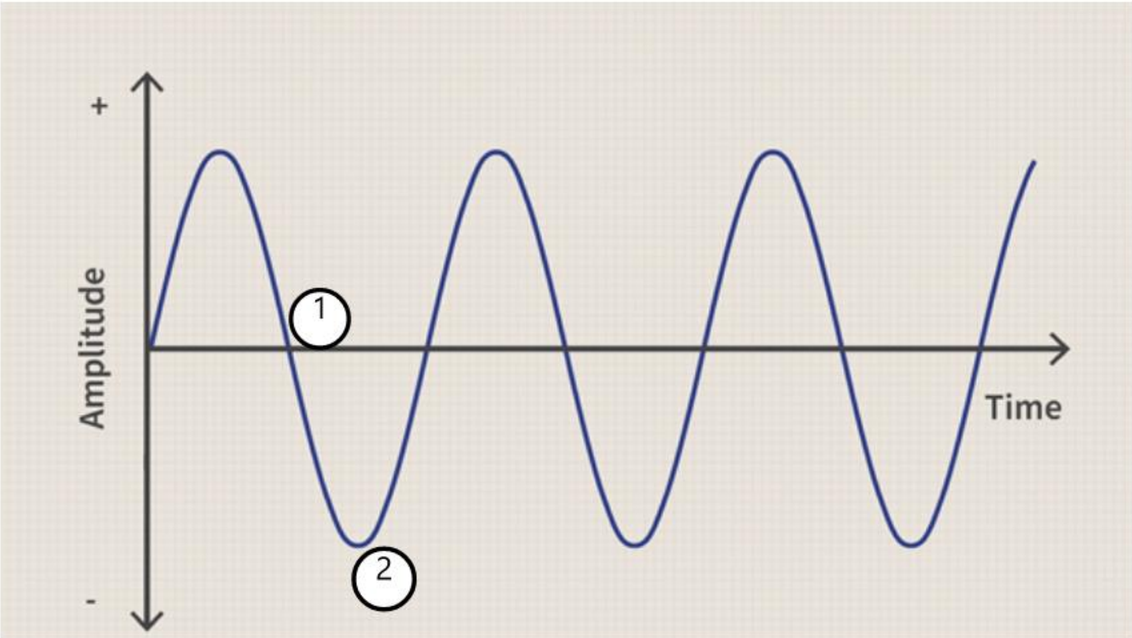

Figure 2-3 Stiffening effects due to slab oscillation

At Position 2, the trapped air is stiffened to the maximum theoretical pressure due to the oscillation of the slab. The time taken for this to occur can be seen to be $\lambda/4$. Therefore, if the time associated with the oscillation of the floating slab to move through ¼ of its total period is greater than the time taken for an acoustic wave to reach the perimeter of the slab and cause local air in that region to "escape" then the stiffening effects due to this trapped air will be reduced. This approximation rule is increasingly true as the delta between the time it takes the acoustic wave to reach the perimeter and the time it takes the floating slab to reach peak negative amplitude is increased.

2.1.3 Typical Methods

Methods observed in industry to approximate the severity of any stiffening effects appear to typically be based on Ungar's equation:

$$Fn(air) = (\frac{1900}{\sqrt{m.d}})$$

Where:

m = mass of the floating floor (and any SDL or LL considered) in kgm^{-2}
d = depth of the void under the floating floor in m

Whilst this simplicity is undeniably useful, it is both dimensionally inconsistent (mass in m^2 and depth in mm) and it assumes that the air gap is sealed.

The following sub-sections present a developmental method which is more applicable to cases when the perimeter of the floating floor slab is not sealed. This is thought important as experience with many floating floors suggests that the air-stiffening effect predicted from the Ungar relationship seldom occurs in practice – i.e. there is usually a naturally occurring 'venting' of the air under the floor.

3 ALTERNATIVE ASSESSMENT

3.1 Step 1 – Calculate Potential for Stiffening Effects Due to Time

By examining the likely period of floating slab oscillation and the dimensions of the floating slab itself, it is possible to determine whether any trapped air has the potential to escape before notable stiffening effects occur.

Continuing the example from above of a 4Hz isolation bearing (with 16mm static deflection) it can be seen that the full period of the floating slab's oscillation will be 0.25 seconds, and hence the air pressure underneath the slab would move from its resting to maximally-compressed state in 0.0625 seconds, assuming it could not escape and the vertical motion of the floor is uniform across its plan area. This is not likely in most practical floors where a degree of 'local reaction' is expected with the floor under localised dynamic load (from a person jumping or dropped weight) yields locally due to the combined effect of non-infinite bending stiffness in the slab and the fact that the bearings are in discrete locations..

Assuming the speed of sound in air to be 340 m/s, the acoustic wave can travel approximately 20m in the time it takes the floating slab to reach peak negative amplitude (i.e. a quarter wave period). Assuming a worst-case condition where the pulse of Z-axis deflection was centered in the middle of a locally reacting floating slab, this suggests that a means to trigger air movement at the perimeter ("venting the slab") will be required if the slab has a dimension of 20m or greater between its center and any point on its perimeter.

For illustrative purposes, this quarter wavelength dimension would reduce to approximately 10m if the bearings had an Fn of 8Hz, and to approximately 5m if the bearings had an Fn of 16 Hz.

3.2 Step 2 – Calculate Potential for Air to Escape into a Reservoir

If Step 1 suggests that the potential for stiffening effects to occur exists, then it is then useful to examine whether surrounding, connected 'reservoirs' of air can accommodate air movement. In real terms, the void underneath the base of a box-in-box solution is commonly coupled to the void between the internal and external box 'sides' and so air can move freely within this combined volume.

This is illustrated below.

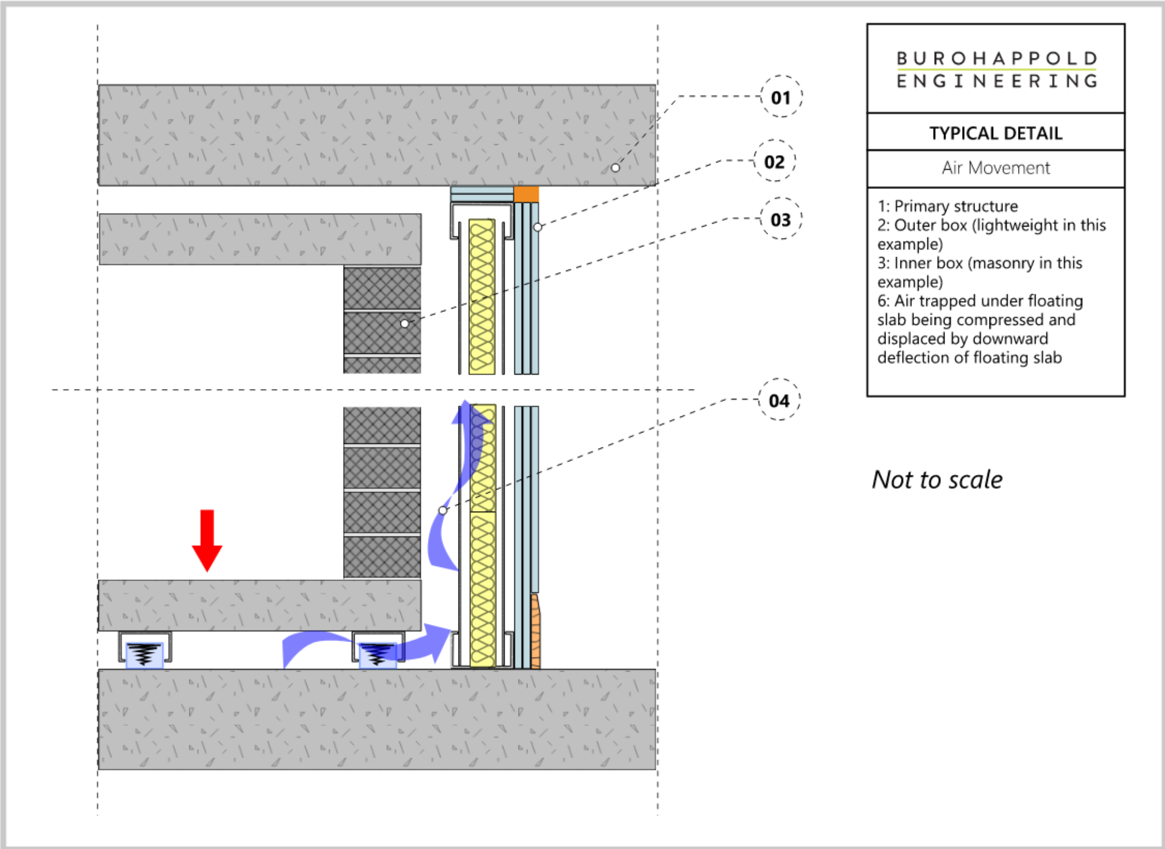

Figure 3-1 Air displacement (indicative)

This assessment is done to the first order of complexity by examining the relative volumes of the void underneath the floating slab, and the void between inner and outer box. These are then combined and equated with the area of the floating slab to give an "equivalent void depth" – i.e. the depth of the void which would be present if the volume between the inner and outer box was added to the volume beneath the slab.

The equivalent void depth can be seen to be significantly contingent on the overall width of the box 'side returns'.

Once this equivalent volume is known, the relative air stiffness of these combined cavities can be compared, using:

$$Fn = \frac{1}{2\pi} \times \sqrt{\frac{K}{m}}$$

Where:

K = stiffness of air (considered to be the adiabatic bulk modulus of air at 140 kPA)
m = mass of the floating floor (and any SDL or LL considered) in kgm^{-2}

Once the Fn of the combined void is known, this can be compared to the Fn of the bearings. If the Fn of the void is lower, then the insertion loss of the system will be principally determined by the Fn of the bearings, given by:

$$\frac{xk}{F_0} = \frac{1}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\,\xi\left(\frac{\omega}{\omega_n}\right)\right]^2}}$$

Where:

ἐ = bearing % damping loss factor
ὠ/ὠn = the ratio of forcing frequency to natural frequency

However, if the Fn of the combined void is > the Fn of the bearings, then stiffening effects are predicted. In this case, to maintain isolation effectiveness, efforts should be made to allow air to escape both the underfloor void **and** the void between the internal and external box. The principles of this are shown below:

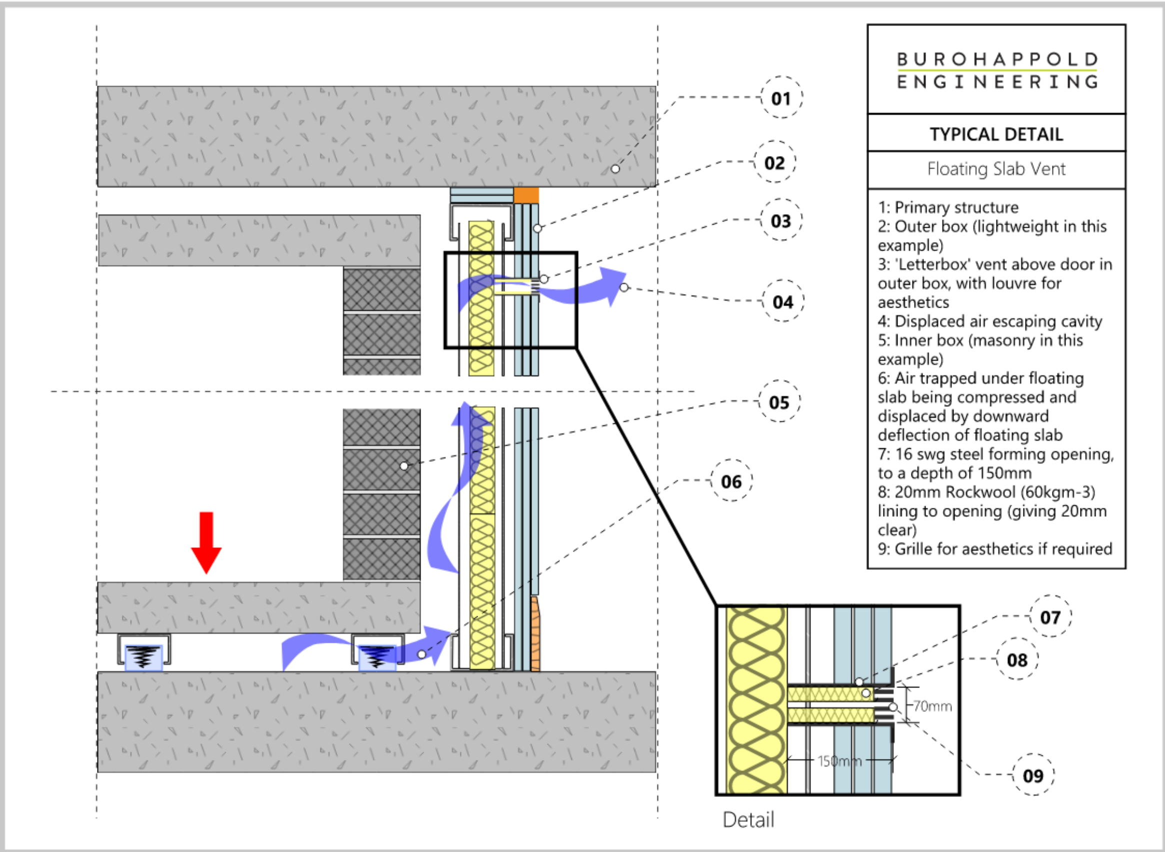

Figure 3-2 Air escape vent (concept)

3.3 Step 3 – Calculate Required Hole Size to Allow Air to Escape

By introducing a vent in the outer box line, the movement of air is permitted into a wider volume, typically a connected circulation space providing access to the space isolated in the inner box.

Whilst anecdotal and experiential accounts indicate that "including a hole" is is an effective strategy, Buro Happold's method provides a means for sizing this opening, noting that being over-generous in the creation of the hole can lead to a significant reduction in composite sound reduction for the outer box leaf, which could be problematic in itself.

The equations used to size the opening are adopted from the traditions of Building Physics, where it is necessary to size the "throat area" of ventilators based on volume flowrate and coefficient of discharge for elements such as openings facilitating cross-ventilation.

The principle equation defining the area required is:

$$A = {q}\Big/{\left(\frac{2\Delta p}{\rho}\right)^{0.5}} \times C_D$$

Where:

A = opening area in m^2
q = volume flowrate in m^3/s
Δp = pressure difference in Pa
ρ = density in kgm-3 (assumed 1.2 kgm^{-3} for air)
V = acceptable discharge velocity in m/s
C_D = coefficient of discharge (taken as 0.3 assuming a grilled finish)

In order to calculate the required volume flowrate for a space, the equivalence of volume flowrate under dynamic deflection being equal to the peak displacement caused by the vertical acceleration associated with the slab's oscillation (multiplied by the area of the slab) is used.

Conservatively assuming the slab to have a response factor of 1 (0.005 RMS ms^{-2}) this means that the peak vertical acceleration is defined as:

$$a = 0.005 \times \sqrt{2}$$

Providing peak vertical acceleration of 0.007 ms^{-2}

With the peak vertical displacement being given by:

$$z = 0.007 \big/ (2\pi.Fn)^2$$

Where:

Fn = lowest natural frequency of isolation bearings

This typically generates a very small number – when employing this new method on real-world projects initially, Buro Happold have typically adopted a pessimistic number to allow for unusually high point live loading on the floating slab, and hence have taken the peak vertical dynamic displacement to be not less than 2mm.

And the subsequent volume flowrate (q) is therefore given by:

$$q = z.a$$

Where:

z = peak vertical displacement

a = floor area of the floating slab in m^2

Inputting the various factors into the equations above therefore provides an area (in m^2) of opening required to permit the volume flowrate required to allow the air trapped under the slab to move freely and avoid stiffening effects.

Although the exact area required for the opening is now known, there are further considerations which can impact the final level of performance. These are expanded upon below.

4 FURTHER CONSIDERATIONS AND FUTURE WORK

4.1 Composite Sound Reduction Index (SRI)

By introducing an opening in the outer box, this can introduce significant weakness in the composite sound reduction performance of this leaf. The calculation of the composite SRI of this single leaf is straightforward and well-understood methods exist for doing so.

However in this instance, the overall composite SRI of both leaves is essentially formed of 3 individual panels – the inner box 'side', the inner box 'floor' and the outer box 'side' (which now includes a ventilation opening).

To date, work involving this method has therefore been based around calculating a composite SRI for the inner box side and base (combined) and estimating a reverberant sound pressure level in the void between inner and outer box, before subtracting the composite SRI of the outer box side and ventilation opening to calculate the resultant sound pressure level in an adjacent circulation space. However, a more elegant method of carrying out this process may well be found.

Case study calculations have typically indicated that the impact on sound transmission between the inner box and circulation predominantly impacts the higher frequencies (500-4000 Hz), and may result in a reduction in performance by approximately 5-10 dB in this frequency zone. This is significant (noting that any reduction obviously depends on the acoustic robustness of the elements before the introduction of the vent, with more robust build-ups being penalised comparatively greater).

However, box-in-box constructions are typically implemented in music performance or fitness developments, where the problematic sound field is typically the lower end of the audible spectrum (63-125 Hz). This means that building fabric (e.g. doors, partitions) making up the outer-box leaf which affected by this reduction in mid-high frequency performance are specified on the basis of their ability to reduce the low frequency sound fields to which they are exposed.

Given that the lower frequencies are invariably harder to attenuate, Buro Happold have found that such build-ups typically over-perform against higher frequencies by default, and therefore that the moderate reduction in mid-high frequency SRI can be tolerated. The improvement in low frequency performance is typically found to be "worth the squeeze", particularly when it is possible to locate the vent on the same wall as the door into the box-in-box space (which represents a comparatively weak element anyway and so suffers less in terms of lost composite SRI).

4.2 Flow Resistance

There is concern the flow resistance could impede the passage of air movement, therefore reducing the effectiveness of the proposed solution. The pressure loss through the opening is given by:

$$\Delta p = 0.5 \times (\rho \times Cd \times V^2)$$

Where:

ρ = density in kgm^{-3}
Cd = coefficient of discharge
V = velocity in m/s

Calculations (following Boyles Law) on case studies to date have indicated that the delta in pressure change due to the vertical deflection of the slab is typically small, but also that the pressure drop across the vent is also small. On this basis flow resistance is not considered likely to represent a significant barrier to the effectiveness of this strategy, however for cases where the vertical deflection of the floor is significant (e.g. bearings with a high degree of dynamic deflection), the coefficient of discharge is low and/or the velocity is low, then this should be checked.

Consideration has also been given to elements within the void between the inner and outer box impeding the free movement of air. The most common material by far encountered to date has been mineral or glass fibre insulation.

The proposed method for avoiding the insulation adding flow resistance to the 'escape' air path has been to omit a strip of insulation equating to the width of the vent opening as shown below.

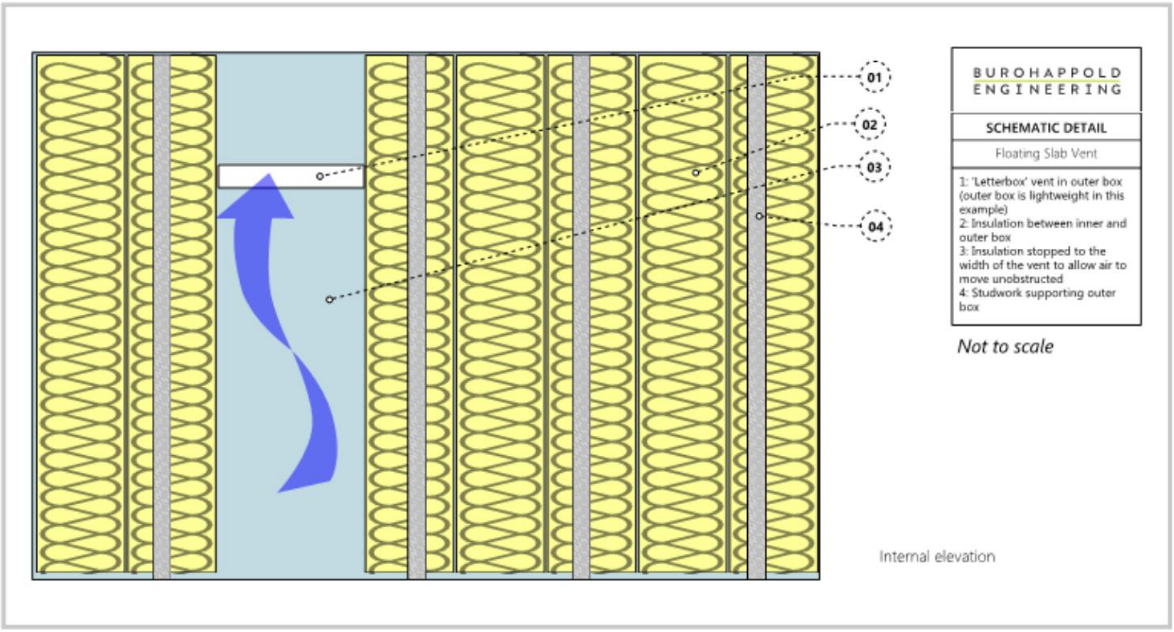

Figure 4-1 Air escape route - clearing the path

4.3 Vent Shape

Although the overall area required for the vent opening is determined in the method described, there is currently no developed proposal for sizing the specific dimensions of the opening. Assuming a "letterbox" slot-type shape, naturally the longer dimension lends itself to increased losses in composite SRI of the external leaf of the box at higher frequencies, and little change is predicted in low frequency (63-125 Hz) composite SRI regardless of whether the height of the slot is 15 or 70mm.

On this basis (and with respect to the types of grille commercially available to finish the opening architecturally), designs to date have fixed 70mm as the height of the grille, with the width being variable to suit the overall open area requirement.

More work remains to be done to investigate this phenomenon – e.g. the influence of circular openings, which are plausible and have the possible benefit of a high coefficient of discharge.

4.4 Vent Location

The absolute size of the floating floor slab has an influence on the selection of the vent's location (assuming that Steps 1 and 2 above indicate that a vent is indeed advisable). The size must be considered in relation to the period of the slab's oscillation.

In the best-case scenario, the situation represented is a floating floor with very compliant bearings, and a very small area. This suggests that the location of the vent is comparatively unimportant. Assuming that the bearings with the lowest Fn commonly specified might be Fn = 3Hz (on the basis that the static deflection associated with even less stiff bearings is architecturally unmanageable), the $\lambda/4$ rule returns a maximum distance of ~28m from the centre of the floor to the vent, which can be accommodated in most developments.

In this example, only very large floating floors which have a radius of >28m from the centre point to the perimeter, may therefore require a vent opening in the slab itself. Introducing an vent(s) in the slab itself transposes the considerations for composite SRI from the outer leaf of the box, to the base of the box and generally shifts the focus from horizontal to vertical sound transmission.

However, if the period of the slab's oscillation is much briefer, due to the higher Fn of the bearings, then there can be considerably less time for the air displacement effects to happen before stiffening occurs. Assuming that the stiffest bearings specified might be Fn = 20 Hz (on the basis that useful low-frequency insertion loss starts to wane above this level of performance), this suggests a $\lambda/4$ rule of ~4.5m from the centre of the floor to the vent, suggesting the need for regular floor vents in large slabs with comparatively stiff isolation bearings, and encouraging a lower specification for bearing Fn.

Similarly, if the vertical height of the outer box leaf is significant and the intention is to locate the vent at the top of the leaf, then the additive effect of increasing the path distance from the centre of the slab to the escape vent should be considered – in this instance it may be necessary to locate the escape vent lower on the outer box wall to reduce the overall distance.