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Estimation of residential noise levels due to service equipment

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Apartment noise has become more in focus recently, and most European countries have strict normative limits, whilst some countries have even stricter voluntary limits. Elevator suppliers work to guidelines for minimizing sound emission from elevator shafts into the residential location, but as with other service equipment, with their moving, sliding and rotating electro-mechanical components, complete silence is not practical. The sound transmitted from elevators though the building tends to be structure borne rather than airborne, but elevator safety codes restrict the flexibility of connections between the elevator structure and the building structure. On the other hand there is a trend in the building industry to optimize building materials, and this brings a challenge to sound insulation. Therefore it makes sense to collaborate with building designers to optimize the acoustic solution for residents. ISO standard EN 12354-5 was used as a basis to create a calculation tool to estimate the structure borne noise in a room behind an elevator shaft wall. Using measured data, transmission through the shaft wall is calculated using power balance methods. Material properties of the shaft wall, acoustic room parameters and excitation force normal to the wall were used to estimate the resulting noise in the room. The calculations have been verified against several test cases and are used by our sales engineers to work with customers to optimize the elevator in its building.

1 Introduction

Apartment noise has become more in focus recently, and most European countries have strict normative limits, whilst some countries have even stricter voluntary limits. Apartment noise maximum limits are set by most countries' Building Regulations. European apartment noise limits vary, but generally range from 30-35dBA (L_{Amax}) and 25 – 28dBA (L_{Aeq}). Many countries have voluntary tiered classifications. Furthermore, recently, acoustic performance inside the building has been considered under environmental assessment methods such as BREEAM [8]. Also most countries have guidelines concerning building material properties, measurement of sound insulations and reverberation times, and noise from installations and service equipment in buildings.

Installations and building service equipment comprise: water systems, heating ventilation and air conditioning systems and elevators which provide essential services to the building. Elevator installations are designed to transport people and goods efficiently, smoothly and safely between building floors. They are critical solutions to an increasingly urbanized and aging society. Along with other building services equipment, they contain electromechanical components that produce airborne and structure borne sound.

Generally elevator suppliers consider noise and vibrations at the following user interfaces: inside the elevator car, at the landings outside the shafts and at the interface to the apartments. To that end, they try to limit the noise of their own components, namely in the machine room, and in the shaft. More commonly in European residential buildings, the machine room has been removed, and all machinery is installed in the shaft. Although this provides the client with much better space efficiency, much of the machinery now is located closer to the residents' apartments. Elevator suppliers work to the guidelines of VDI2566 [1], which recommends maximum allowable airborne and structure borne noise and vibration values, and gives guidelines on both elevator and building design.

Our own experience has shown us that noise transmission from the elevator shaft into the resident's apartment is predominantly structure borne. First obvious solutions to eliminating structure borne noise are: (1) eliminate the source (2) isolate the transmission (3) build a thicker shaft wall (4) add absorbent coverings in the receivers room. Whilst all these solution are possible they come at a price: (1) completely eliminating the source for an average elevator consuming 5-10kW of power is possible, but expensive (2) Isolating the elevator from the adjoining wall is also possible, but the isolation elements must be rigid enough to carry the elevator working forces and also abnormal forces which need to be catered for by safety codes. This somewhat limits the flexibility of the isolation elements and therefore reduces isolation efficiency. (3) Builders are as cost conscious as any other industry and are looking at reducing the shaft wall thicknesses, rather than increasing them. (4) Acoustically absorbent coverings or double skin walls need to be at least 50mm thick to be effective, thereby reducing the resident's useable space and adding cost.

To achieve an economically efficient and low noise solution to structure borne transmission involve good elevator and building design early in the design process. This was the background to creating this estimating tool. The tool was designed to help our elevator sales engineers to optimize the elevator within the context of its building.

2 Prediction challenge

Figure 1 shows a simplified arrangement of a typical Machine Room Less elevator in a shaft. The electro-mechanical and mechanical components run along guide rails which are fixed to the shaft wall via brackets. The guide rails and brackets need support the elevator loads during normal running conditions and abnormal events, stated in the elevator safety codes [2].

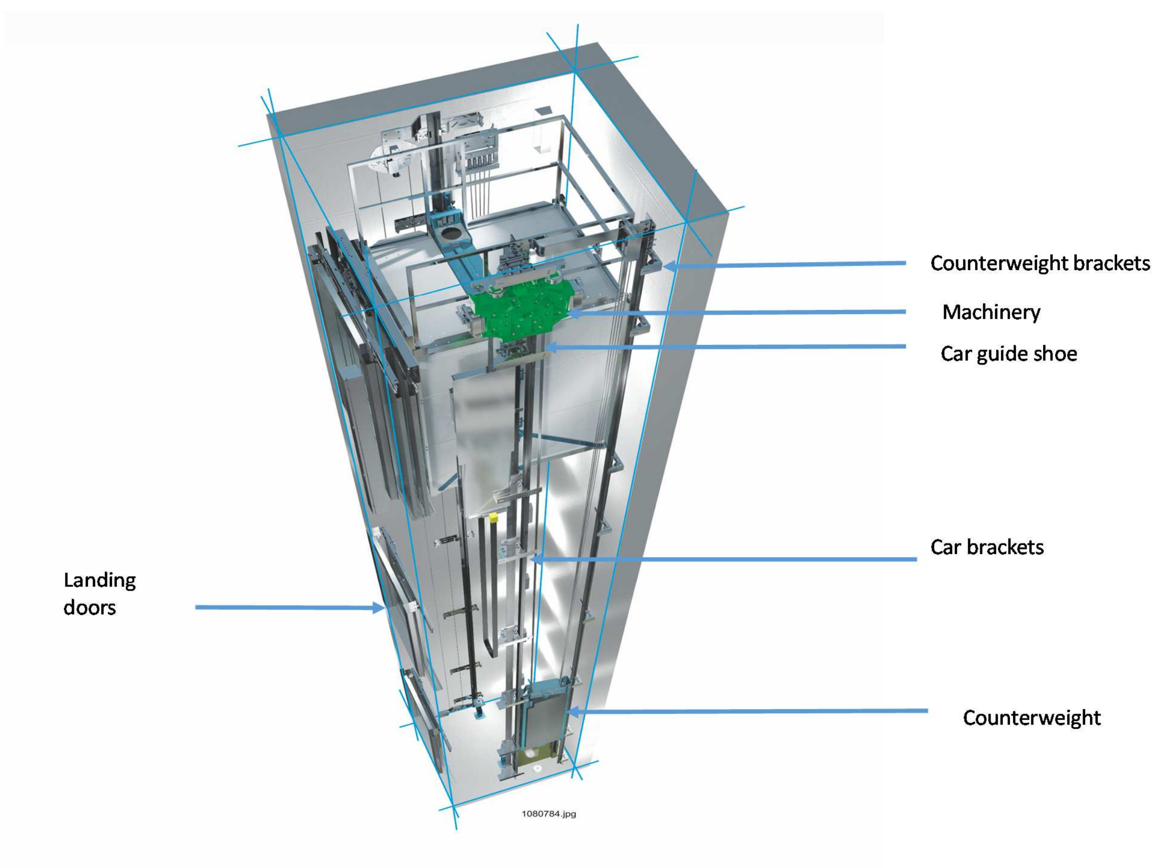

Figure 1: Machine Room Less (MRL) elevator in a shaft.

This 3D figure can be further simplified to an arrangement of the transmission path from the inside of an elevator shaft into an adjacent room. Basically for efficient transmission of sound energy from source to receiver, a mechanical path is needed. The mechanical path, being the critical wall as well as flanking wall convert the vibrations generated on the elevator shaft side, Figure 2.

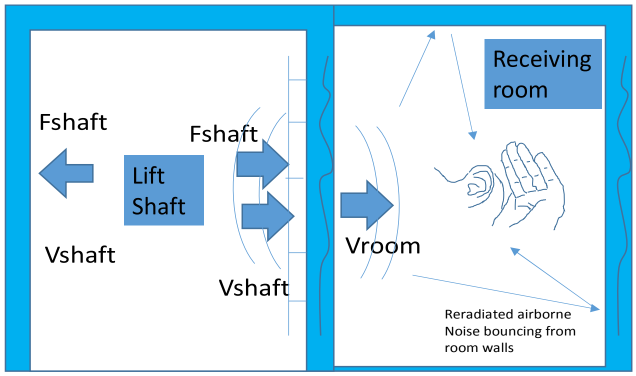

Figure 2: The critical structure-borne noise path from the shaft to an adjacent receiving room.

The European standard EN 12354-5:2009 [3] defines calculation models to estimate the sound pressure level in buildings due to service equipment, including lifts. Clause 4 of the standard deals with methods for structure-borne transmission through building construction. The problem is depicted in a schematic way in Figure 3. L_W is structure-borne sound power injected into the wall.

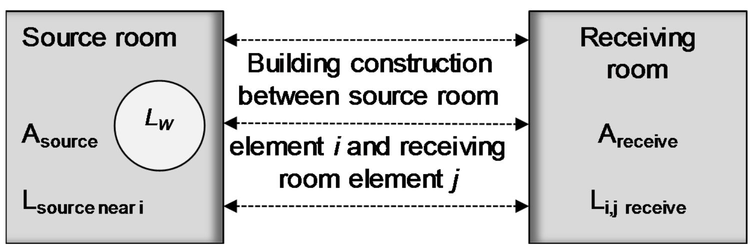

Figure 3: Schematic representation of the structure-borne sound transmission as presented in [3].

However, there are some limitations in the standards that make the results too approximate to be used practically. For example when considering lift installations, the standard [3, p. 34] estimates an uncertainty in the source input data of 4dB, and uncertainty in transmission prediction of 3dB. Total uncertainty without considering inaccuracies in the receiver's room side calculations would be therefore 7dB. When considering apartment noise limits of 30-35dBA, 7dB is quite a large uncertainty, even without considering inaccuracies on the receiver room side. Furthermore the standard proposes just one set of characteristic sound power levels for a lift machine on elastic supports, when in reality there are several other components emitting structure borne sound in the shaft, and these levels vary very much depending on the elevator's speed and load rating. This led us to refine the model based on EN 12354-5:2009 [3], backed with detailed FE- and SEA -calculations, measurements and empirical data.

3 Methods

3.1 Standard EN 12354-5

Equation in the Annex I.2 of the EN 12354-5:2009 expresses the normalized (“n”) sound pressure level $L_{n,s,ij}$ in a receiving room for each path *ij* (direct or flanking):

$$L_{n,s,ij} = L_{Ws,inst,i} - D_{sa,i} - R_{ij} - 4 \tag{1}$$

$L_{Ws,inst,i}$ is the installed structure-borne sound power level of the source, $D_{sa,i}$ is the adjustment term form structure-borne to airborne excitation and R_{ij} is the flanking sound reduction index in dB defined in [4]. The adjustment term $D_{sa,i}$ in (1) is

$$D_{sa,i} = 10\log(\eta_i) - R_i + 10\lg\left(\frac{2\pi f\, m_i}{\varrho c}\right) - 10\lg(\sigma_i) \tag{2}$$

For the direct path R_i = R_{ij} and then

$$L_{n,s,ij} = L_{Ws,inst,i} - 10\lg(\eta_i) - 10\lg\left(\frac{2\pi f\, m_i}{\varrho c}\right) + 10\lg(\sigma_i) - 4 \tag{3}$$

η_i is structural loss factor of the wall, m_i is the surface mass of the wall (kg/m^2), ϱc is the characteristic resistance of air (400…420 Pa s/m) and σ_i is the sound radiation efficiency of the wall.

It is a bit challenging to use the above equations directly. First, the physics behind them is not apparent. This a typical problem for equations expressed in logarithmic form (i.e., decibels). The second, fundamental challenge is that the installed structure-borne sound power level is needed as input and therefore it needs to be determined.

3.2 Verification of the EN 12354-5 equations

Equation (3) can be verified as follows. Power-energy balance for a wall with surface area S_i and surface mass m_i is [6]

$$W_{s,inst.i} = 2\pi f\, \eta_i\, E_{kin,i} = 2\pi f\, \eta_i\, m_i\, S_i\, \langle v_i^2 \rangle \tag{4}$$

Radiated sound power $W_{Rad,i}$ of one side of the wall at frequency *f* is

$$W_{Rad,i} = \rho c\, \sigma_i\, S_i\, \langle v_i^2 \rangle = \frac{W_{s,inst.i}\ \rho c\, \sigma_i}{2\pi f\, \eta_i\, m_i} \tag{5}$$

In the latter part of (5), area-averaged squared velocity $\langle v_i^2 \rangle$ and wall area S_i are eliminated using (4). Equation (5) in logarithmic form is

$$10lg\left(W_{Rad,i}\right) = 10\lg\left(W_{s,inst.i}\right) - 10\lg\left(\frac{2\pi f\, m_i}{\rho c}\right) - 10\lg\left(\eta_i\right) + 10\lg(\sigma_i) \tag{6}$$

Reverberant sound pressure level in a room as a function of sound power is [7]

$$L_p = L_{W,Rad,i} + 10\lg\left(\frac{4}{R}\right) = 10\lg\left(W_{Rad,i}\right) - 10\lg(10^{-12} Watts) + 10\lg\left(\frac{4}{R}\right) \tag{7}$$

In (7), the distance dependent part of sound pressure level (i.e., direct sound field) is omitted. Substitute $10\lg(W_{Rad,i})$ from (6) into (7). After some manipulation

$$L_p = 10\lg\left(\frac{W_{s,inst.i}}{10^{-12}}\right) - 10\lg(\,\eta_i) \; - 10\lg\left(\frac{2\pi f \; m_i}{\rho c}\right) + 10\lg(\,\sigma_i) - 10\lg\left(\frac{R}{4}\right) \tag{8}$$

If the room constant *R*=10, then the last term is $10\lg\left(\frac{R}{4}\right) \approx 4$. Thus, equation (8) verifies equation (3).

3.3 Wall structural input power

Direct measurement of structural input power is challenging. Methods are usually based on the equation (9) for point force input power.

$$W_{s,int,i} = \frac{1}{2}|F^2|Re(Y) \tag{9}$$

F is the magnitude of force and *Y* is the mobility of the wall. The standard [3] does not provide explicit methods for power input determination. It merely mentions that methods include

- Reception plate technique [5]. A calibrated laboratory test rig is used to measure input power via energy balance. Then result is corrected for the mobility of in-situ structure. The force is assumed to be constant. This is a structure-borne equivalent for sound power determination using a reverberation chamber.
- If the source can be decoupled from the wall, one is able to measure free velocity and mobility of the source. Then one can estimate the force exciting the wall by combining the information to a suitable mobility model including the coupling elements
- In the case the source is essentially a force source the power follows from known force and wall mobility. However, the standard does define explicitly how to use this option

In the present case, the source cannot be connected to a calibrated receiver. Neither can it be measured in a free, uncoupled state. Hence, use of experimentally extracted forces and theoretically derived wall mobilities are the only feasible way.

3.4 Experimental determination of forces

The characteristic bending mobility Y_∞ of a wall as a thin plate can be estimated as [6]

$$Y_\infty \approx \frac{1}{2.3\rho_m \, c_L \, h^2} \tag{10}$$

ρ_m is the wall material density (kg/m^3), c_L is the speed (m/s) of longitudinal waves in the wall material and h is the wall thickness (m). The characteristic mobility is essentially a space- and frequency average of the discrete point mobility. It can be used to approximate the mobility.

Forces are still needed. The procedure used by the authors is as follows

1. Measure the point mobilities Y= v’ / F’ of a wall at force contact points using hammer or shaker excitation.
2. Measure wall operational vibration velocities v at the same contact points
3. Extract the operational forces from F = v/Y

The operational force(s) can then be applied for other walls with different properties to estimate the power input from (9) and then sound pressure level from (3) or (8).

Some raw data from measurements at eight points is shown in Figure 4. There are certain issues in scaling the forces from multiple points to a single effective force. The topic is beyond the scope of this paper. A conservative estimate of effective force is used in production calculations.

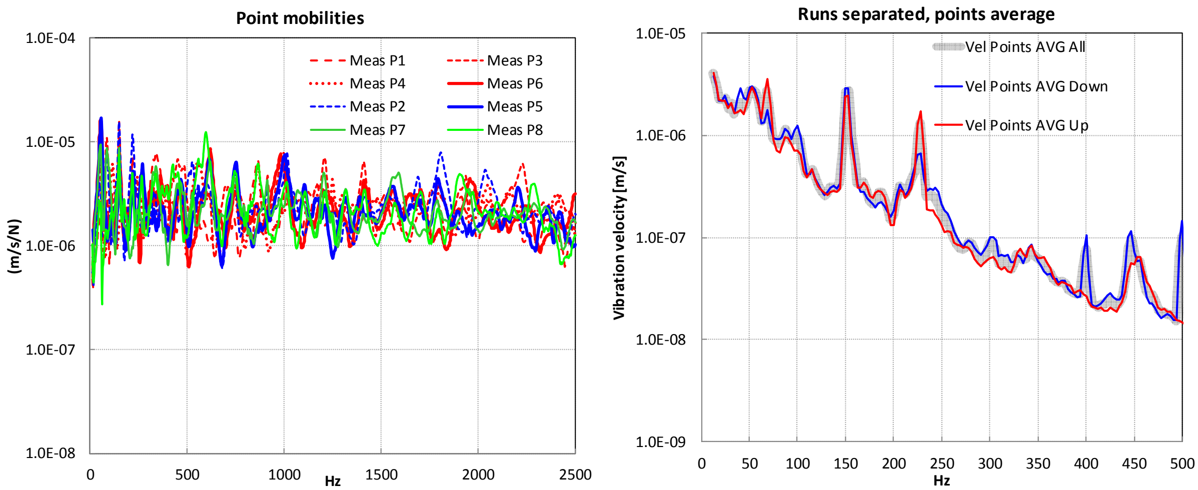

Figure 4: Wall point mobility- and vibration velocity measurement raw data.

4 Estimation tool

An estimation tool based on above equations (4) to (10) was created. Calculations are conducted at 1/3-octaves from 20 to 2000 Hz. The wall and receiving room parameters as well as excitation forces are given as input. The output is receiving room total sound pressure level and the 1/3 octave spectrum. Note that the calculated sound pressure level is spatial average of the reverberant sound field and, in the present version of the tool, does not include the direct sound field of the radiating wall.

As a first test, the tool was used to calculate structure-borne sound spectra in a small receiving room “Koppi”. The forces and receiving room reverberation times were available. At this point, two different approximations (LOW, HIGH) were used for the forces. The results for the elevator going full speed down are in shown in Figure 5.

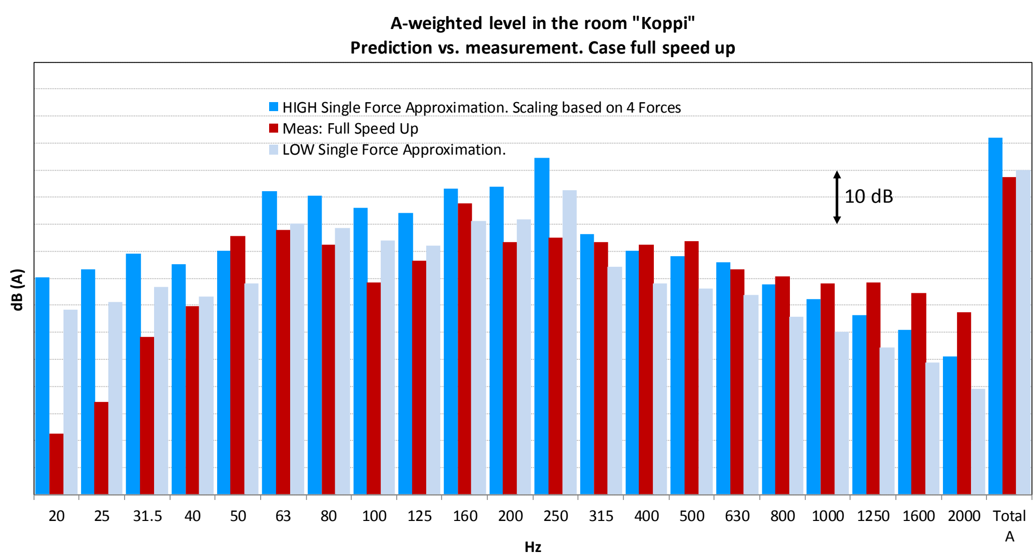

Figure 5: Results of a test case concerning receiving room “Koppi” behind a 150 mm concrete wall.

The overall A-weighted noise level in the receiving room is well predicted, as are the levels at most individual frequency bands between approx. 63 and 1000 Hz. At lowest frequencies the predicted levels tend to be above those measured. The probable reasons to this are that (a) the equation for characteristic mobility in equation (10) is not valid at the lowest frequencies, (b) statistical room acoustics used in equation (7) does not work well at low frequencies and (c) wall direct- or near field effects.

At highest frequencies above 1000 Hz, accuracy of the equation (10) assuming pure bending is not very good. The thick plate effects (shear deformation) start to be significant and the input power is increased.

The calculations were expanded to cover common ranges of speeds and loads of selected European residential elevator platforms, common shaft wall materials and thicknesses and common residential living room sizes and absorption rates. The calculations were verified against several real cases. The tool has enabled our elevator sales engineers to better understand the effects of different elevator and building configurations, and help our customers optimize at the beginning of the building designing stage.

5 Concluding remarks

Elevator installations are designed to transport people and goods efficiently, smoothly and safely between building floors. They are critical solutions to an increasingly urbanized and aging society. Along with other building services equipment, they contain electromechanical components that produce airborne and structure borne sound. Our own experience has shown us that noise transmission from the elevator shaft into the resident's apartment is predominantly structure borne.

To achieve an economically efficient and low noise solution to structure borne transmission involves good elevator and building design early in the design process. This was the background to creating the estimation tool. The tool based on EN 12354-5 with some our own refinements was designed to help our elevator sales engineers to optimize the elevator in the context of the building.

The tool has been applied on common ranges of speeds and loads of selected residential elevators, common shaft wall materials and thicknesses and common residential living room sizes and absorption rates. The results have been good. The average total observed uncertainty has been approximately 4 dB, much less than the value stated in the standard [3].

Topics of further development include taking into account the radiating wall direct- and near-field contributions in the receiving room as well as treatment of thick or non-homogenous walls.

Acknowledgement

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