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ON THE RELEVANCE OF IMPACT SOURCE IMPEDANCE AT LOW FREQUENCIES - PART 2: FLOORS WITH FLOATING TOPPINGS

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Low frequency noise generated from impact sources on floors is becoming more significant due to the trend of using lighter building components. The amount of sound power that gets injected into the floor depends on the impedance matching between the source (e.g. barefoot or shoe walkers) and the receiving surface (e.g. floor). In a previous study, it was identified that the impedance of the impact sources at low frequencies has no influence on the power injected into wood or concrete floors without floating toppings. The reason is because the impedance of both the wood and concrete floor is much higher than the source impedance and only the force controls the amount of power injected into the floor. In this current study, calculation models are used to simulate the effect of a floating topping on the injected power by investigating the resulting impedance and impedance match between the floor with a floating topping and the two standardized ISO impact sources (heavy/soft ball and hard tapping machine). Finally, the relevance of impact source impedance at low frequencies will be presented for floors with floating toppings.

Keywords: building acoustics, impact sound, low frequencies, impedance match

Introduction

The bigger goal of this study is to identify whether impact measurement using both the standard tapping machine (ISO 10140-3) and the standard ball (ISO 10140-3) are necessary to better characterise floors for impact sound at low frequencies (50-500 Hz octave bands). For this paper, the standard tapping machine and standard ball will be referred to as "Hammer" and "Ball" respectively. In order to broaden the scope, airborne sound insulation results referred to as "Airborne" and measured according to ISO 10140-2 also will be include.

The improvement and differences in improvement between the three sources (Airborne, Hammer and Ball) were determined through measurements with nominally the same floating topping placed on 5 different floors: three cross laminated timber (CLT) floors, one concrete floor, and one wood I-joist floor described in Section 3 below.

Although the measurement methods used and type of data gathered for the three sound sources are quite different, comparisons seem to give acceptable results. For example the Airborne excitation is steady state, the Hammer excitation is quasi-steady state, and the Ball excitation is transient; all with different signal analysis.

In a first step to understanding the effect of adding a topping, a simple mass-spring-mass model (topping-interlayer-floor) is used. With this model, the resonance frequency at which the topping becomes decoupled from the floor is calculated as well as the improvement expected below this resonance frequency due to adding a topping.

The main purpose of this paper is however not to investigate how large the improvement is due to the added topping, but to investigate what portion of the improvement is due to the impedance match between the sources and floor with a topping. If it can be shown that there is no significant difference between the power injected into the floors with toppings by the various sources (at the low frequency range) the sources are redundant and only one source should be necessary. As this study only includes a small set of floors the results can only be applied to this set and not extended to a general statement.

Power Injected

The Power injected is defined by

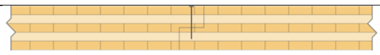
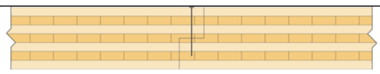
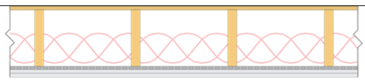
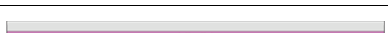
$$P_{inj} = 1/2F_0^2\Re\{Z_f\}/|Z_f + Z_S|^2 \tag{1}$$

where F_0 is the blocked force of the source and Z_s and Z_f are the impedances of the source and floor respectively. The power injected is greatest when the impedance of the source is the complex conjugate of the impedance of the floor, in other words, when the magnitude of source and floor are equal and their phases are opposite. Here, the later part of Eq. 1 only dependent on the impedances will be called normalized Power $P = \Re\{Z_f\}/|Z_f + Z_S|^2$ and compared later in Section Normalized Power Injected. The estimates used to describe the impedances of the sources and floors are described in Sections Sources and Floor: Parallel Plates.

Specimen Description

Five different base floor (3 x CLT, 1 x concrete, 1 x wood I-joist) assemblies were tested all with and without nominally the same floating topping consisting of 38 mm gypsum concrete on a 9 mm foam interlayer. A short code, the mass per area m'', the longitudinal propagation speed c_L, and thickness are given in Table 1 below. The properties of the floating topping which varied slightly for the different base floors as also seen in the table.

Table 1: Floor specimen descriptions. Mass per area m''_2 of wood I-joist floor is given for just OSB subfloor and the full floor. Actual property values of topping varies between specimen. Total mass per area m''_{tot} including floating topping is given in most right column.

Code	Base Floor	m''_2 in $\mathrm{kg/m^2}$ mass per area	c_L in $\mathrm{m/s}$ long. speed	h in mm thickness	m''_{tot} in $\mathrm{kg/m^2}$ mass per area
CLT131		67	3000	131	170
CLT175		91	3000	175	194
CLT245		130	3000	245	220
CON150		378	3400	150	467
WI235		9.4-37	2700	235	90
Floating Topping on 9mm interlayer with dyn. stiffness 35-50 $\mathrm{MN/m^3}$					
GCON38		(m''_1) 81-103	3000-3400	38	

Measurement Methods

The data used in this study was collected at the National Research Council of Canada (NRC) across several studies in the NRC Floor Sound Transmission Facility which is described in [6]. Note that, throughout the paper, results of third octave band data for the Ball are presented as fast weighted peak levels ($L_{iF,max}$) according to ISO 10140-3, for Airborne as sound reduction index (R) according to ISO 10140-2, and for the Hammer as normalized impact sound pressure level (L_n) according to ISO 10140-3.

Analytical Models

The analytical models were chosen without damping for the floors to simplify the calculations and to ensure the differences seen in normalized power injected into to floor are maximized. Without damping, the resonances of the floor impedance will be more pronounced and have sharp peaks leading to a large reduction of the floor impedance. This means the magnitude of the impedance of the sources and floors become more similar in magnitude which should will lead to more power being injected - a conservative estimate.

Sources

The impedance of the hammer was estimated as $Z_h = j\omega m_h$, with $m_h = 0.5\ kg$ being the mass of a hammer, $j = \sqrt{-1}$, and ω the angular frequency. The impedance of the ball was estimated using a parallel mass-spring-damper system approach

$$Z_B = \frac{1}{1/Z_m + 1/(Z_s + Z_d)} \tag{2}$$

with $Z_m = j\omega m_B$ and $Z_s = \frac{s}{j\omega}$ and $Z_d = \eta_B$. The mass of the Ball was measured as, $m_B = 2.5\ kg$; and the stiffness $s = 40E3\ N/m$ and the damping $\eta_B = 71.3\ Ns/m$, were estimated using an elegant method [5] in which the Ball dropped onto a rigid surface is modelled using simple mass-spring-damper system. With this model the stiffness and damping properties of the ball are obtained through a formulation that as input data simply requires the number of bounces until the ball is stationary and the total duration of this process. The impedance of air was simply assumed as the characteristic impedance of a plane wave $Z_a = \rho c$, using the density $\rho = 1.2\ kg/m^3$ and the wave propagation speed $c = 340\ m/s$.

Floor: Mass-Spring-Mass

The simple mass-spring-mass model that can be found in many textbooks [7] was applied here to simulate the dynamics of the topping-interlayer-floor system. In the equation describing the resonance frequency $f_0 = 1/(2\pi)\sqrt{s(1/m_1 + 1/m_2)}$, above which an improvement due to decoupling of the two masses is expected, the topping is described with Mass 1 (m_1), the spring with Stiffness s, and the base floor with Mass 2 (m_2).

The impedance of the floors is not calculated here using the mass-spring-mass model because the idealized model without damping allows no power to be injected as the impedance has no real part (see Eq. 1). The mass merely changes the phase of the velocity and creates only reactive power and no apparent power.

Floor: Parallel Plates

To model the floor with the floating topping, Cremer's model [3] that describes two infinite parallel plates surrounding a spring-like interlayer is utilized. A point force excites the upper of the two plates, both of which are assumed to support only bending waves due to neglecting rotary motion and sheer deformation. As will be shown, although the assumption of a point force excitation is far from accurate for airborne insulation, the model still delivers reasonably good results. In the model, the top infinite plate simulates the topping and the bottom plate the base floor.

The vibration of the top plate v_1 from which the (drive-point) impedance ($Z_f = F_0/v_1(0)$) can be calculated by setting the excitation at point $r = 0$ as describes by:

$$v_1(r,\omega) = \frac{F_0}{Z_{1\infty}}\left[A_{11}\Pi(k_{C1}r) + A_{12}\Pi(k_{C2}r)\right] \tag{3}$$

where $Z_{1\infty} = 8\sqrt{B_1'm_1''}$ is the impedance of the free infinite plate. The impedance the bottom infinite plate if vibrating freely would be $Z_{2\infty} = 8\sqrt{B_2'm_2''}$.

The wave propagation function

$$\Pi(k_A r) = H_0^{(2)}(k_A r) - H_0^{(2)}(-jk_A r) \tag{4}$$

having both a near- $H_0^{(2)}(-jk_A r)$ and far-field $H_0^{(2)}(k_A r)$ term. At drive point ($r = 0$) the wave propagation function $\Pi(0) = 1$.

The wavenumbers k_{C1} and k_{C2}, both present on the top (topping) and bottom plate (base floor) can be describe as:

$$k_{C1,2}^4 = \frac{1}{2}(k_{B1}^4 + k_{B2}^4)\sqrt{\frac{1}{4}(k_{B1}^4 + k_{B2}^4)^2 + k_{A1}^4 k_{A2}^4 \frac{\omega_1^2\omega_2^2}{\omega^4}} \tag{5}$$

Theses wavenumbers are dependent on the wavenumbers of a free plate, $k_{A1,2}^4 = \frac{m_{1,2}''}{B_{1,2}'}\omega^2$, and of the blocked plate, where the plate is on an springlike interlayer on an infinitely rigid foundation $k_{B1,2}^4 = k_{A1,2}^4(1 - \frac{\omega_{1,2}^2}{\omega^2})$.

The point excitation is described by $p = F_0\delta(x)\delta(y)$, whereby the resonance frequencies are $\omega_{1,2} = \sqrt{\frac{s''}{m_{1,2}''}}$, and the coefficients A_{11}, A_{12}, A_{21}, and A_{22} are defined as:

$$A_{11} = \frac{k_{A1}^2}{k_{C1}^2}\frac{k_{C1}^4 - k_{B2}^4}{k_{C1}^4 - k_{C2}^4}; \quad A_{12} = -\frac{k_{A1}^2}{k_{C2}^2}\frac{k_{C2}^4 - k_{B2}^4}{k_{C1}^4 - k_{C2}^4}; \tag{6}$$

$$A_{21} = \frac{k_{A1}^2}{k_{C1}^2}\frac{k_{A2}^4}{k_{C1}^4 - k_{C2}^4}; \quad A_{22} = -\frac{k_{A1}^2}{k_{C2}^2}\frac{k_{A2}^4}{k_{C1}^4 - k_{C2}^4}; \tag{7}$$

The (drive-point) impedance necessary for calculating the normalized injected power can easily be calculated by rearranging Eq. 3 to

$$Z_f = \frac{Z_{1\infty}}{A_{11} + A_{12}} \tag{8}$$

Results

In this section, both the measured improvement due to adding the topping and the calculated normalized power injected dependent on floor and source will be presented and discussed.

Improvement

The difference between levels of insulation with and without the 38 mm floating gypsum concrete topping are shown in Fig. 1. A positive value means improvement of sound insulation of the floor due to adding the topping.

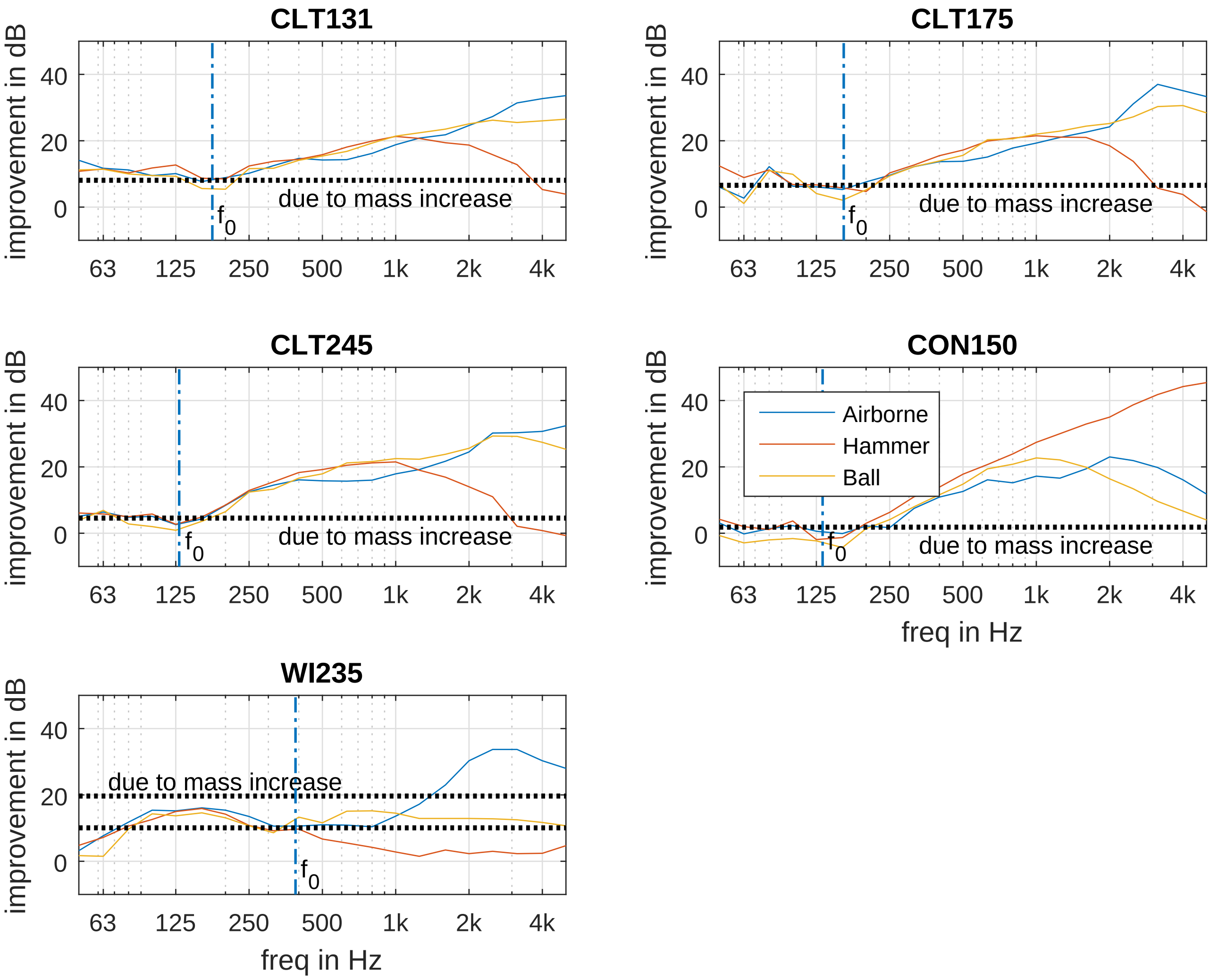


Figure 1: Improvement due to adding nominally the same topping on different floors.

Figure 1 shows that improvement due to the topping is very similar for all sources at low frequencies, independent on which floor it was added to. The dashed horizontal lines depict the improvement expected purely due to an increased mass $(20\log(1+m_1/m_2))$ of the floor. This improvement is only expected to be valid below the mass-spring-mass resonance f_0 of the system. For the wood I-joist floor (WI235) two horizontal lines describe the expected improvement assuming an effective mass per area of the full floor (bottom line) and of only the OSB (top line) sub-floor layer. The measured improvement due to the added topping lies somewhere in between.

Above the resonance frequency f_0 calculated using the mass-spring-mass model and marked by the blue vertical line, the improvement begins for all sources on most floors, yet the improvements diverge for the different sources at higher frequencies. This is partly due to the different impedance matching of the floor and sources.

Impedance

Before looking at the calculated normalized power injected, the magnitude and phase of the impedance of the floors and sources calculated with the parallel plate model will discussed in Fig. 2.

The phase of impedance of all base floors is null as the impedance ($Z_{2\infty}$) has only a real part (see Section Floor: Parallel Plates). The phase of the floors with topping vary between null and π and cross null at the mass-spring-mass resonance. The phase of the impedance is quite different for each

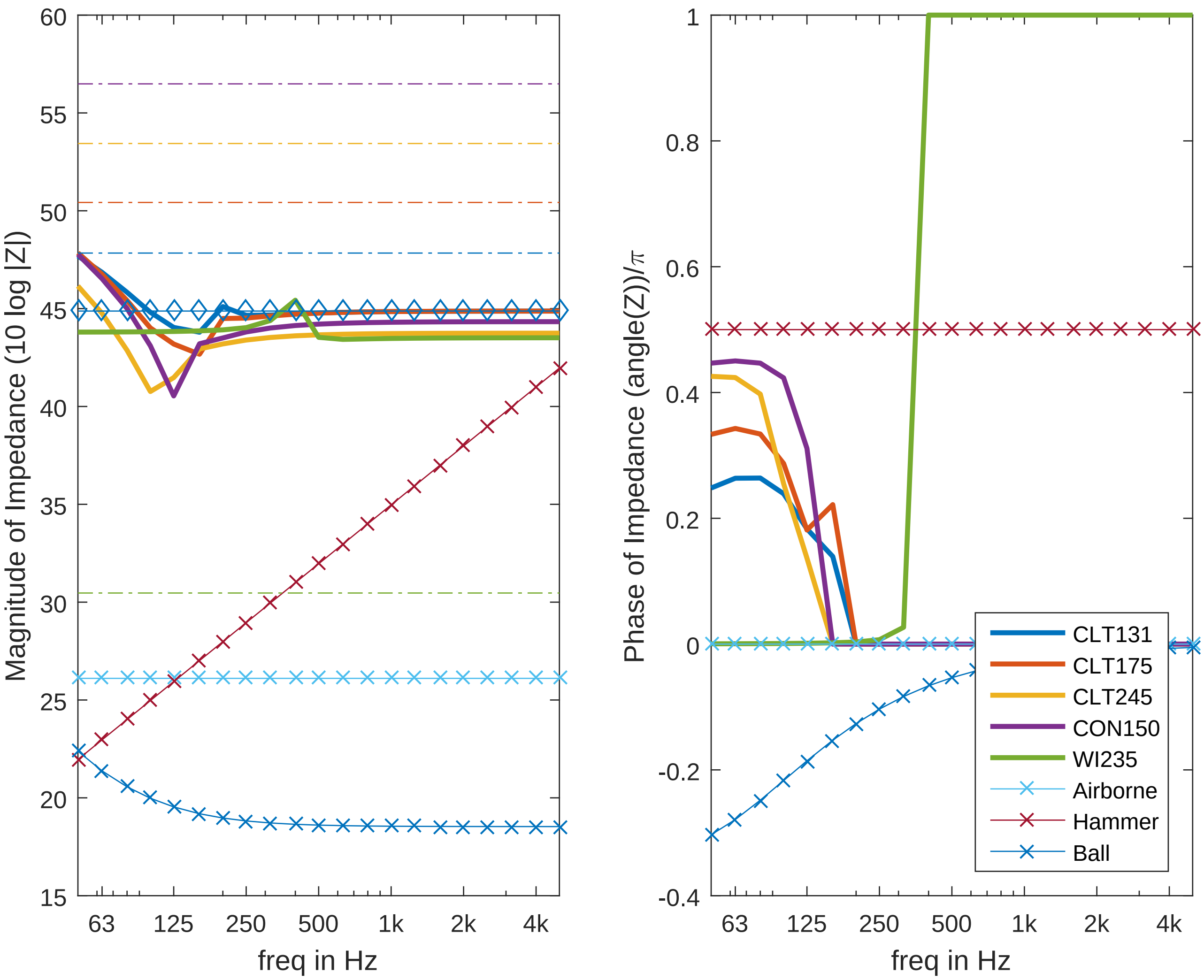


Figure 2: Impedance of floors and sources. Left: $10\log(|Z|)$, right: phase(Z). Dashed lines depict impedance of base floor assemblies without topping. Solid lines depict impedance of floor assemblies with topping. Diamond-markers depict impedance of one of the five toppings and X-markers depict sources.

of the three sources. The Hammer being modelled as an ideal mass has the phase $\pi/2$, whereas the phase of Airborne excitation is null, and finally the phase of the Ball impedance moves from stiffness controlled (negative number) to null.

It can be seen that the magnitude of impedance of the base floors is much higher than that of the three sources in the low frequency range. Only at about 500 Hz does the impedance of the Hammer, rising at 3 dB per Octave come close to the impedance of the lightest floor without topping (WI235-green dashed line). By adding the topping, the impedance of the all floors except the WI235 floor drops rapidly towards higher frequencies and matches that of each corresponding topping (blue diamonds for CLT131) above the resonance frequency. This is because above the resonance the topping is decoupled from the floor and the source can only see the topping as if it where free. This still leaves the impedance of the floors with topping much larger than that of the sources until approximately 5k Hz at which the Hammer impedance almost reaches the floor impedance with topping.

The impedance of the wood I-joist floor, WI235, reacts opposite to the other floors: by adding the topping the impedance increases, as the impedance of the floor (OSB) is much lower than that of the gypsum concrete topping. Thus leading to less power injected into floor WI235 with topping than without.

In other words the impedance of the floors with topping is still much larger than the source impedance, so, only the blocked force will contribute to the magnitude of the injected power. This coincides with the results seen in the measurements - the improvement for all sources were very similar at the low frequency range.

Normalized Power Injected

Figure 3 now shows the normalized power injected into the bare floor relative to the floor with topping calculated using the parallel plate model. A positive number means more normalized power is injected into the bare floor. Note that the power injected is into the whole system and does not directly relate to how much normalize power continues to the base floor through the topping. For the cases without topping, the impedance of an infinite plate $Z_{2\infty}$ was used to describe the base floor.

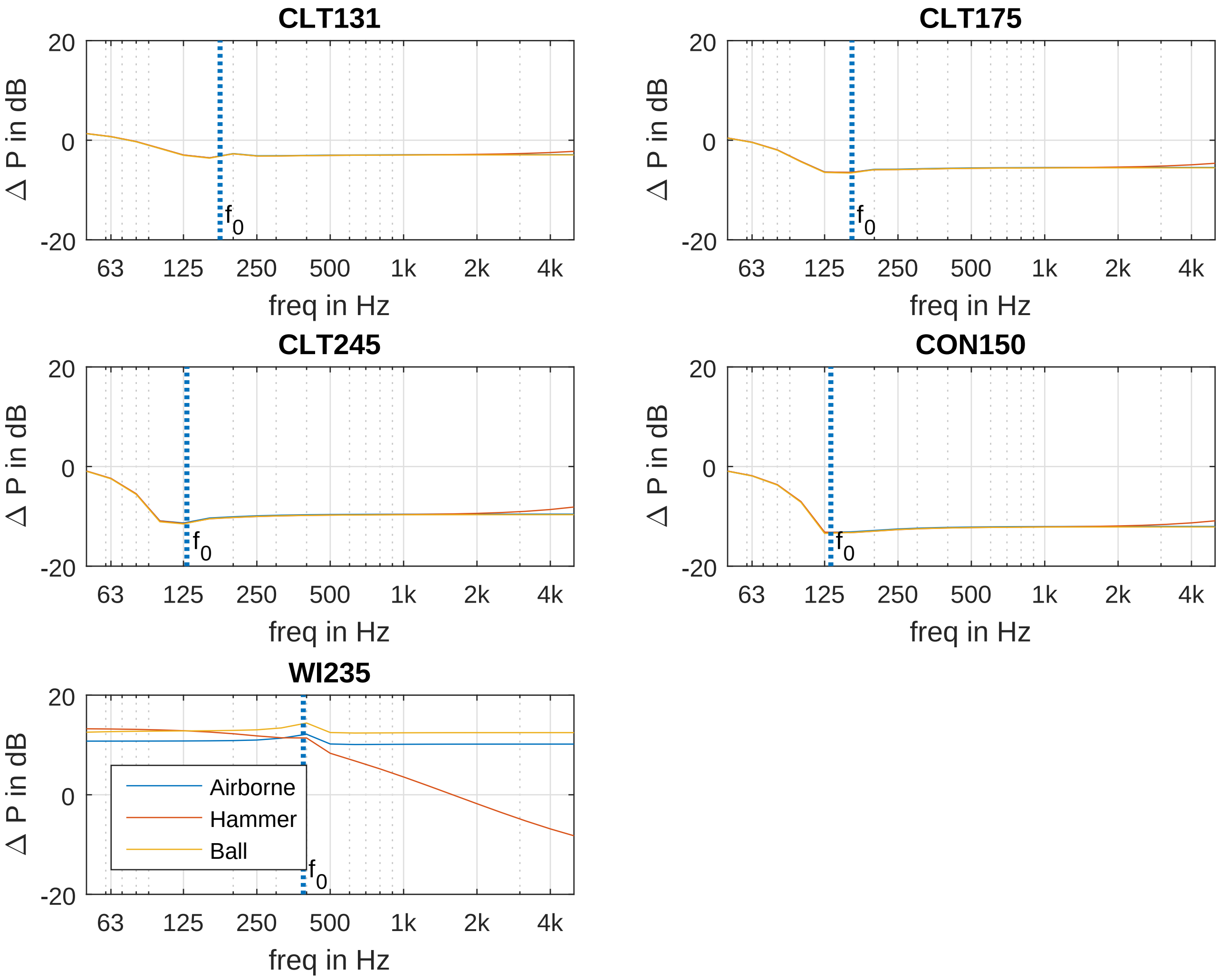


Figure 3: Normalized power injected into the bare floors relative to with topping. A positive number means more normalized power gets injected into the bare floor. A negative number means more normalized power gets injected into the floor with topping.

One can see that for all of the floors except WI235, less normalized power is injected into the floor with a topping than without over the entire frequency range. This is because with the topping the impedance of the floor is reduced and closer to that of the source leading to more injected normalized power. For the WI235 the impedance of the floor increases due to adding the topping leading to less normalized power being injected by the sources with the topping.

With the calculation model used, the difference between the change in normalized power injected into the floors due to adding the topping for all of the sources can be neglected, except on the wood I-joist floor (WI235). However, here the effect on the different sources is not significant until above approximately 500 Hz which is due to the impedance matching between the source and the floor that was described above. The Hammer injects more power into the OSB subfloor at the higher frequencies than into the gypsum concrete topping. Also, for WI235 floor, the Airborne source reacts quite differently to the impact sources and injects less power due to the impedance miss-match.

The differences seen in the measurement of improvement (see Fig. 1) between the sources at high frequencies above 2k Hz is most likely due to the contact stiffness of wooden floors as reported in other papers [4]. That was not included in this impedance model. However, these effects are only of concern in the upper frequency range and not part of this investigation.

Summary and Conclusions

It was shown through measurements that the effect of adding a floating topping on very different massive and lightweight floors is not significantly different for Airborne, Hammer and Ball excitation. Simplified models describing the impedance of the sources and floors with and without the floating topping were used to estimate how much power was being injected into the floor due to a source-receiver impedance match. The theoretical calculations agreed well with the measured data in the low frequency range and also showed that the impedance of the source for the types of floors and toppings tested have no influence on the results.

So, for the floors with floating toppings investigated in this study the results imply that only one impact sources needed to correctly characterize the floor at low frequencies!

Outlook

In the future, a larger set of floors with toppings having lower and higher resonance frequency with more or less damping will be investigated. The studies will also be extended to even lower frequencies where the Ball impedance rises. Also, the absolute improvement will be looked at by using the transfer-impedance (from topping to base floor) instead of the drive-point impedance as used here.

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