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Improvement of impact sound insulation: a constitutive model for floating floors

Alessandro Schiavi

INRIM – National Institute of Metrological Research, Strada delle Cacce, 91, 10135 Torino, Italy

ABSTRACT

Floating floor is one the most effective building technologies for noise protection in dwellings, since it greatly reduces the vibrations transmission through structures. Acoustical performance of a floating floor is quantified in terms of improvement of impact sound insulation *ΔL*. The improvement of impact sound insulation of a floating floor is a key parameter for the calculation of structure-borne sound insulation in buildings. Indeed, once *ΔL* is known, it is possible to evaluate the impact sound insulation, in *in situ* conditions, for several base floors of different building technologies and materials. *ΔL* can be directly determined on the basis of standard laboratory measurements, but it can be also estimated from elastic and inertial properties of involved materials, such as stiffness and mass. In this paper a constitutive model for the estimation of floating floors improvement of impact sound insulation is presented. As it will be shown, the constitutive model proposed based on force transmissibility theory, allows to accurately estimate the acoustical behavior of a floating floor, as a function of frequency, with a simple single function. Theoretical assumptions, experimental evidences and comparisons with previous computational models (e.g., Cremer-Vér model) allow to confirm both validity and effectiveness of the proposed model.

1.Introduction

Sound insulation in buildings is a fundamental requirement for *comfort* and *privacy* in dwellings. Moreover, in many countries worldwide, laws, regulations and directives state limits for airborne and structure-borne sound insulation, as well as façade insulation and equipments noise, for both newly developed buildings and existing buildings (renovation); acoustical classifications, similarly to thermal classification, are also proposed [1-5]. As a consequence, accurate evaluations of acoustical performances of buildings are needed in order to address suitable solutions for noise protection. Acoustical properties of building elements, such as walls, floors, windows and involved materials can be measured in laboratory, accordingly to current Standards (e.g., ISO 10140 series) or estimated on the basis of several computational models (e.g., EN 12354 series). Acoustical performances can be evaluated as a function of different conditions of installation and, nowadays, many *software* of building acoustic performance simulation are commercially available. Analytical derivation of these computational models, based on Reyleigh's theory [6], were developed in last century in particular by Cremer [7], Beranek [8], and Fahy [9].

This paper is focused on the calculation model for improvement of impact sound insulation *ΔL* of floating floors. As it is well-known, Cremer-Vér calculation model allows to evaluate the acoustical behavior of a floating floor as a straight line, with a slope of 30 dB (or 40 dB) per decade of frequency (in one-third octave band), starting from the resonance frequency of the analogous mass-spring system. In general terms it can be considered such as “mass-law” behavior, since improvement of impact sound is only determined for frequencies above the resonance frequency. Acoustical behavior around and below the resonance frequency is neglected, or simply assumed as $\Delta L=0$.

An alternative approach for the calculation of the improvement of impact sound insulation of floating floors, based on force transmissibility theory [10], is presented. Proposed constitutive model allows to accurately evaluate the actual insulation effectiveness of a floating floor, as a function of frequency, by means of a single analytical function. In particular the acoustical behavior in the low frequency range is properly achieved.

Measurements of improvement of impact sound insulation, performed in standard laboratory, are modelled with Cremer-Vér model and with the transmissibility model and comparisons are commented.

2. Floating floor technology

A floating floor consists of a floating slab (commonly concrete or lightened concrete) decoupled from the base floor by means of a continuous resilient layer. In general terms it can be represented as a mass-spring-dampener system on a inertial support base, in which the mass is the floating slab and the spring (and dampener) is the continuous resilient layer. In Figure 1 a typical example of a floating floor system and the related mechanical model is schematically depicted. It is supposed that the floating slab is uncoupled from lateral walls. Reduction of impact sound pressure level can be empirically estimated on the basis of elastic and inertial properties of involved materials. In particular if elastic (and damping) properties of the resilient layer are accurately determined and the mass per unit area of the floating slab is known, the improvement of impact sound insulation of a floating floor, can be achieved.

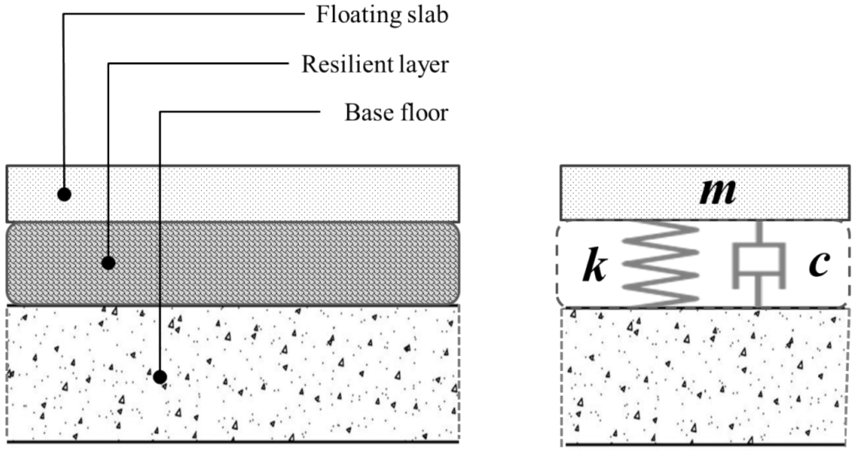

Figure 1: Section of a floating floor built on a concrete base floor and the mechanical model, in which resilient layer is defined by its stiffness (spring of elastic constant *k*) and damping (dampener of dissipative constant *c*) and the floating slab by its inertia (mass *m*).

3. Empirical models: theoretical background

Improvement in impact sound insulation of a floating floor ΔL, defined by Gösele in 1949 [11], is the difference between the sound pressure level, L_{n0}, produced in the receiving room due to the impacts on the supporting bare floor, and the corresponding sound pressure level L_n, due to the similar impact on the floating floor, i.e. $\Delta L = L_{n0} - L_n$, as currently used in scientific literature and technical standards. The empirical model for predicting improvement of impact sound insulation ΔL of floating floors derived by Cremer in 1952 [12], is based on the theory of parallel plates continuously coupled by elastic interlayer [7] and, at present day, is collected in EN 12354-2 Standard [13]. On the other hand, due to the mechanical properties of the mass-spring-dampener system (i.e. the floating floor), the motion of the mass induced to an input force (i.e. the vibration generated by impacts) and transmitted on the base floor by means of a continuous elastic interlayer, can be empirically modelled in terms of force (or velocity) transmissibility.

3.1 Cremer-Vér model

The fundamental Cremer's result, without going into details of analytical demonstration, shows that the improvement of impact sound insulation of a floating floor is provided by the following «surprisingly simple» relation for the «locally reacting» floating floors, i.e. where the slab is highly damped or is infinite:

$$\Delta L = 40\log\left(\frac{f}{f_0}\right) \text{ dB} \tag{1}$$

in which the resonance frequency f_0 of the floating floor only depends on the inertial and elastic properties of the floating slab and resilient layer, as follows:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{s'}{m'}} \text{ Hz} \tag{2}$$

where s' ($\mathrm{N \cdot m^{-3}}$) is the dynamic stiffness of the resilient layer and m' ($\mathrm{kg \cdot m^{-2}}$) is the actual mass per unit area of the floating slab.

Over the years, as recently summarized by Hopkins [14], Cremer's model has been further investigated and refined, in particular by Vér [15, 16], and several experimental works, until present day, allowed to verify its robustness and effectiveness [17-29]. For many floating floors, relation (1) tends to overestimate ΔL and the frequency dependence is better described by the following relation for the floors, where the floating slab is «resonantly reacting»:

$$\Delta L = 30\log\left(\frac{f}{f_0}\right) \text{ dB} \tag{3}$$

As shown by Cremer, in a floating floor atop a base structural floor, ΔL is independent both of the flexural stiffness and mass of the base floor and is also independent of the flexural stiffness of the floating slab: the improvement of impact sound pressure level insulation ΔL can be determined «without knowing anything about the radiation process and the acoustical properties of the receiving room». Previous assumptions allows to confirm that attenuation of the transmitted noise, generated by the vibrations velocity filed in the structural floor, only depends on the mechanical properties of the resilient layer and on the mass of the floating slab.

3.2 Transmissibility model

On the basis of above-described boundary conditions, improvement of impact sound insulation of a floating floor can be accurately modelled in terms of force (or motion) transmissibility, as a typical vibration insulation system model. As a matter of fact, a floating floor can be considered a damped single-degree of freedom system and, in particular for small motions, the system is linear. When the floating slab is excited by a tapping machine, it can be considered a vibrating structure as a whole acting on a foundation (i.e. the base floor) by means of a continuous resilient support. The amplitude of transmitted vibration to the base floor is controlled by the inertia of the vibrating mass and by the elastic (and damping) response of the resilient layer. As a consequence, transmitted vibratory motion in terms of force or velocity, is reduced as a function of frequency, as described in the following well-known force transmissibility relation, T_f:

$$T_f = \frac{F_t}{F_i} = \sqrt{\frac{1+\eta^2\left(\frac{f}{f_0}\right)^2}{\eta^2\left(\frac{f}{f_0}\right)^2 + \left(1-\frac{f^2}{f_0^2}\right)^2}} \tag{4}$$

where F_t is the transmitted force to the base floor, F_i is the input force acting on the floating slab (e.g., due to the impact hammer of a tapping machine), f_0 is resonance frequency, depending on dynamic stiffness of the resilient layer and on the mass per unit area of the floating slab, as shown in relation (3), and η is the total loss factor, i.e. the dissipated energy.

In transmissibility relation (4), beyond the elastic response of the resilient material, also its dissipative behavior, in terms of total loss factor η, is taken into account. In physical terms, total loss factor η is the ratio between the internal damping and the critical damping, $\eta = c/c_c$.

Ten times the logarithm of the square of the reciprocal ratio of these two force amplitude describes the insertion loss (also called the “insulation effectiveness”), of a spring-like device in terms of force (or velocity), in analogy to similar ratio commonly used in airborne acoustic [7]. Acoustic radiation in the receiving room is then due to the reduced vibration velocity of the base floor only. Achieved sound reduction can be expressed, from the reciprocity principle [30], as:

$$10\log\left|\frac{F_i}{F_t}\right|^2 = 10\log\left|\frac{v_1}{v_2}\right|^2 = 10\log\left|\frac{1}{T_f}\right|^2 = -20\log\left|T_f\right| \ \text{dB} \tag{5}$$

Where v_1 is the vibration velocity of the floating slab, v_2 is the reduced vibration velocity of base floor and T_f is the transmissibility function, relation (4). The transmitted sound pressure level directly depends on the vibration velocity level, as shown by Fahy [9], from Reyleigh’s theory [6].

It is possible to demonstrate that, if damping effects are neglected, i.e. $\eta \to 0$, the analytical function obtained from relation (5) corresponds to the function obtained from Cremer's relation (1), for frequencies above the resonance frequency, as follows:

$$-20\log\left|T_f\right| \equiv 20\log\left|1-\frac{f^2}{f_0^2}\right| \approx 40\log\left(\frac{f}{f_0}\right) \ \text{dB} \qquad (6)$$

and by analogy, for floors where the floating slab is resonantly reacting, the frequency dependence of relation (5) is proportional to Cremer-Vér relation (3), as follows:

$$-15\log\left|T_f\right| \equiv 15\log\left|1-\frac{f^2}{f_0^2}\right| \approx 30\log\left(\frac{f}{f_0}\right) \ \text{dB} \qquad (7)$$

Nevertheless in this form, the transmissibility functions are not defined at resonance ($f=f_0$) and tend to 0 for frequencies below the resonance frequency ($f<f_0$), while Cremer-Vér relationships keep constant its slope.

On the other hand, if total loss factor η is known, transmissibility function is defined at each frequency and the improvement of impact sound insulation can be accurately achieved. Indeed, the dissipative effect of resilient materials is relevant in comparison to the dissipative effect in the floating concrete slabs and cannot be neglected [31, 32], whereas in the model derived by Cremer-Vér [15], relation (3), only dissipative effects in the floating slab are taken into account [33]. On average, in resilient materials used in these applications, the total loss factor η is in the order of $\sim 10^{-1}$ and in concrete it is $\sim 10^{-2}$.

As a consequence, the improvement of impact sound insulation ΔL of a locally reacting floating slab, can be estimated on the basis of following constitutive relation:

$$\Delta L = -20\log\left[\sqrt{\frac{1+\eta^2\left(\frac{f}{f_0}\right)^2}{\eta^2\left(\frac{f}{f_0}\right)^2+\left(1-\frac{f^2}{f_0^2}\right)^2}}\right] \ \text{dB} \qquad (8)$$

and for floors where the floating slab is resonantly reacting, the improvement of impact sound insulation ΔL it is expected to behave as:

$$\Delta L = -15\log\left[\sqrt{\frac{1+\eta^2\left(\frac{f}{f_0}\right)^2}{\eta^2\left(\frac{f}{f_0}\right)^2+\left(1-\frac{f^2}{f_0^2}\right)^2}}\right] \ \text{dB} \qquad (9)$$

In the graph of Figure 2 the theoretical comparison between Cremer-Vér model, relation (3), and transmissibility constitutive model, relation (9), is shown, as a function of normalized frequency, f/f_0, for several values of total loss factor η, from 0.01 up to 0.3.

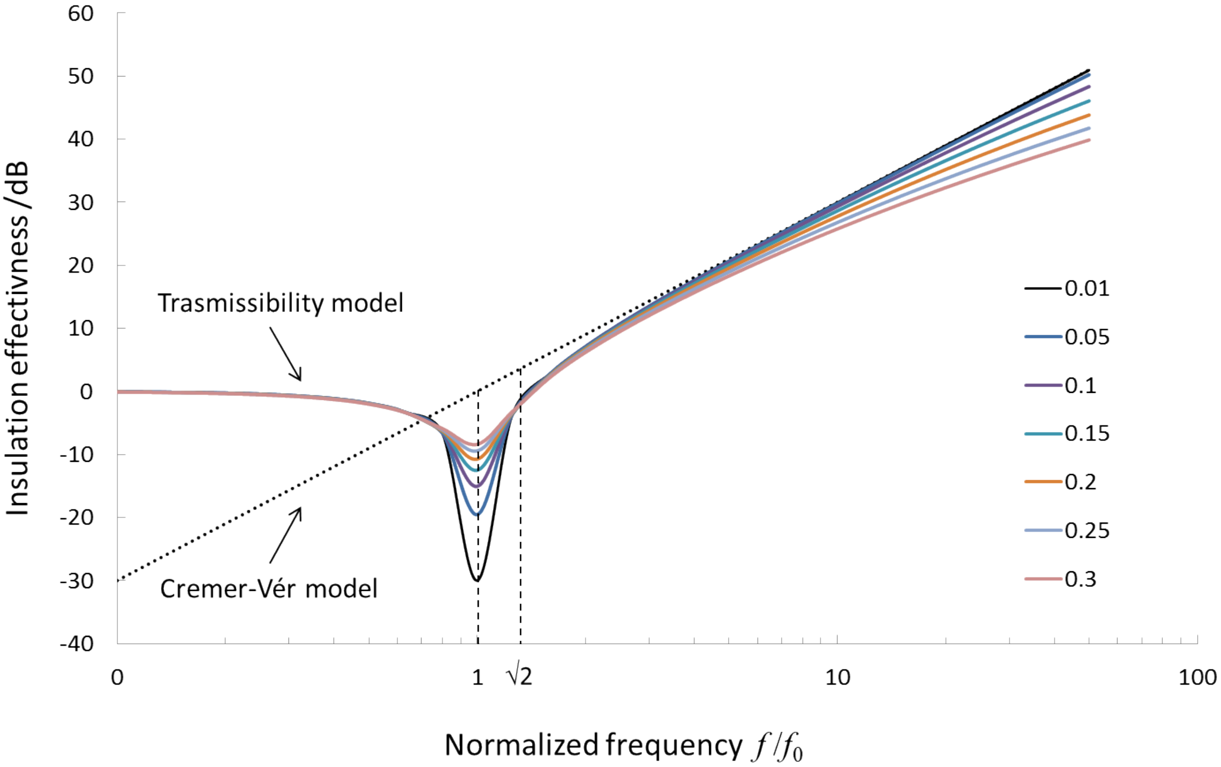

Figure 2: Comparison between transmissibility constitutive model (continuous lines) and Cremer-Vér model (dotted line) and, as a function of normalized frequency.

As depicted in the graph of Figure 2, for frequencies above the resonance frequency, in particular for $f \geq \sqrt{2} \cdot f_0$, and for low values of total loss factor (e.g., 0.01÷0.1), the slope of the transmissibility model perfectly matches with Cremer-Vér model, increasing of 30 dB per decade, as expected. Quite different slopes, of about 27÷25 dB per decade, are achieved for higher values of total loss factor (e.g., 0.2÷0.3). Besides, at the resonance frequency ($f=f_0$), the transmissibility model allows to quantify the resonant amplification effects, as a function of damping. Below resonance ($f<f_0$) and in the low frequency range ($f<<f_0$), no insulation effectiveness is achieved, as commonly assumed [14] and observed [34], i.e. $\Delta L=0$.

Similar behavior is obtained for locally reacting floors, as defined in relation (1) and relation (8), but in this case, for high values of total loss factor (e.g., 0.2÷0.3), the transmissibility model slopes increase of about 37÷35 dB per decade, for frequencies above the resonance.

4. Experimental methods and materials

In order to verify the effectiveness of the constitutive model, experimental data of improvement in impact sound insulation are compared with data estimated on the basis of transmissibility. Measurements of sound pressure levels are performed, according to ISO 10140-3 [35], in the normalized laboratory of impact sound (according to ISO 10140-5 [36]). Requirements of instrumentation are in agreement with ISO 10140-1 [37] and a traditional standard tapping machine is used as impact source.

Transmissibility model is implemented on the basis of mechanical properties of resilient layers actually used. Elastic response of resilient materials is measured on the basis of dynamic stiffness, according to ISO 9052-1 [38], and damping behavior is determined from the width of the frequency response function at resonance peak, by applying the *half-power bandwidth method*.

Measurements are performed on six floating floors built in laboratory. Resilient materials, used as interlayers, are realized with different materials, with different mechanical properties and technical features.

4.1 Laboratory measurements of improvement of impact sound insulation

Measurements of the improvement of impact sound insulation are performed in the normalized laboratory at INRIM. A concrete monolithic floor is the reference base floor, thickness 140 mm, density 2500 kg/m^3. In each laboratory test the floating slabs are realized in concrete or lightened concrete, surface 10 m^2. Data of mass per unit area of each floating slab are shown in Table I. Measurements are performed after 28 days of floating slab curing time. In Figure 3 the normalized laboratory and the tapping machine used, are shown.

Figure 3: Normalized laboratory of impact sound insulation at INRIM: the reference base floor and the standard tapping machine.

Measurements are performed in the frequency range of 100 Hz – 5 kHz. In the receiving room both the sound pressure level, due to the impacts on the supporting bare floor and the corresponding sound pressure level, due to the similar impacts on the floating floor, is measured. The acoustical performance of the floating floor is determined in terms of improvement of impact sound insulation ΔL, on the basis of the difference between the normalized impact sound pressure level measured on the bare floor, L_{n0}, and on the floating floor under investigation, L_n, i.e. $\Delta L = L_{n0} - L_n$. Experimental data of improvement of impact sound insulation, measured in the normalized laboratory, are shown in the graphs of Figure 8 – 10.

In Table I a brief description of resilient materials used as interlayers, the basic technical properties and the mass per unit area of the floating slabs actually used in each test, are shown. Thickness of resilient materials is measured under load (200 kg/m^2), according to EN 12341 Standard [39].

Table I: Samples description and properties

Sample	Description	Density /kg·m^{-3}	Thickness /mm	Mass per unit area of floating slabs m_t /kg·m^{-2}
1	Glass fibres + polypropylene tissue protective sheet	97.8	1.51	78
2	Polyester fibres + bituminous protective sheet	39.4	3.54	100
3	Cork and rubber grains	420.4	5.65	95
4	Rubber fine grains (recycled tyres)	849.6	5.12	105
5	Polyurethane foam (embossed surface)	32.1	4.65	60
6	Polyurethane foam (smooth surfece)	35.7	4.92	88

4.2 Material properties

Mechanical properties of the samples are accurately investigated in terms of dynamic stiffness, according to standards ISO 9052-1 and literature [40-44]. Airflow resistivity of open pore samples is measured according to ISO 9053 Standard [45]. Dynamic stiffness is evaluated on the basis of the resonance frequency measurement of the fundamental vertical vibration of the mass-spring system (loading mass-resilient interlayer). In Figure 4 the dynamic stiffness measurement set-up is shown.

Samples 1 and 2 are high porosity (~0.96) fibrous material coupled with protective rubber-kind sheets; samples 3 and 4 are low porosity (~0.40) compacted grains sheets; samples 5 and 6 are flexible and low density closed cells elastomeric material sheets. All samples are commercially available resilient materials used in floating floor for impact sound insulation. In Figure 4 six tested samples are shown.

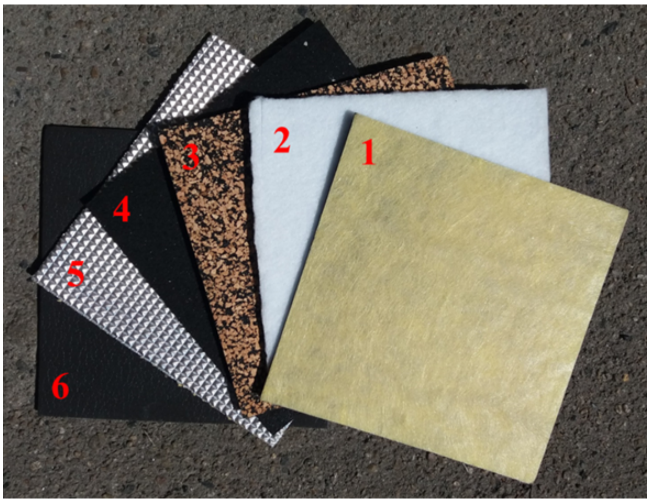

Figure 4: Samples of tested resilient layers.

The sample of resilient layer (400 cm^2) is placed between an inertial base and the loading mass (m_t=200 kg/m^2); on the sample surface a thin layer of plaster of Paris is applied in order to compensate for all irregularities at the surface. Measurements of dynamic stiffness are performed after two weeks of loading time, in order to avoid any possible creep effect in the resilient materials [46-49]. In Figure 5, the dynamic stiffness measurement set-up is shown.

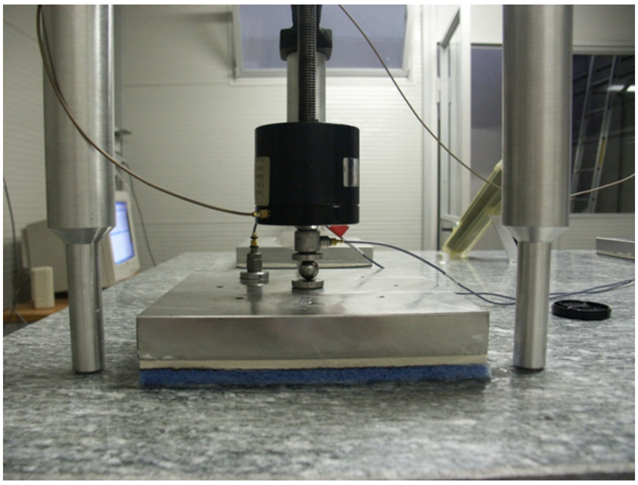

Figure 5: Dynamic stiffness measurement set-up.

The resonance frequency f_r is determined from the Frequency Response Function (FRF) of the fundamental vertical motion of the loading mass-resilient material system, as shown in the graph of Figure 6. By measuring resonance frequency, it is possible to evaluate damping behavior as well, from the width of the resonance peak. Total loss factor η (where $\eta = \Delta f/f_r$) is evaluated on the basis of *half power bandwidth method*. The frequency values $\Delta f = f_2 - f_1$ are determined, on the resonance frequency peak, at – 3 dB from the maximum level (i.e. √2 of amplitude in linear scale), as shown in the graph of Figure 7.

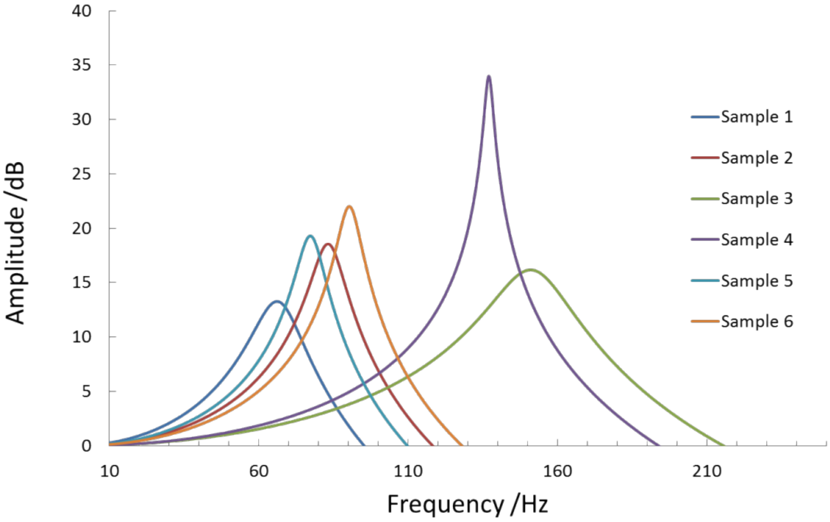

Figure 6: Frequency Response Function of the measured resonance frequencies.

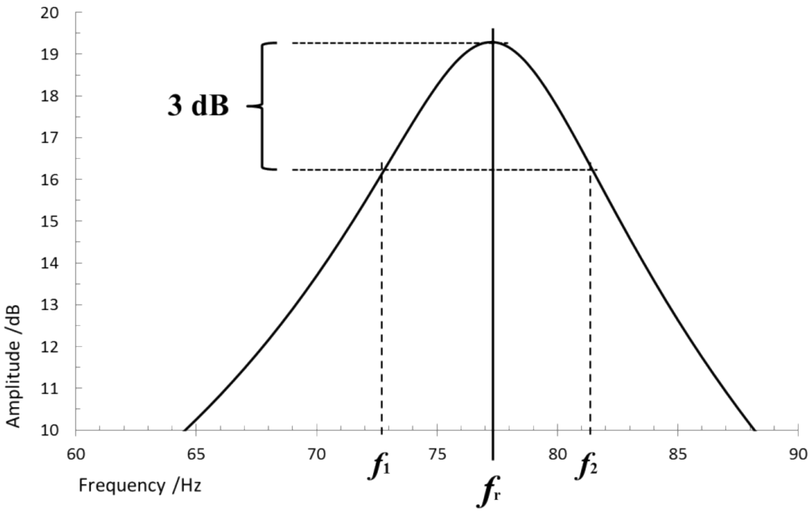

Figure 7: Total loss factor evaluation, on the basis of the *half power bandwidth method*.

Once FRF resonance frequency f_r is determined (experimental data are shown in Table I), dynamic stiffness of tested materials is calculated from the following relation:

$$s' = (2\pi f_r)^2 \cdot m_t \quad \text{Hz} \tag{10}$$

where f_r (Hz) is the measured resonance frequency and m_t (kg/m^2) is the mass per unit area of the loading mass.

From dynamic stiffness s' of resilient materials and mass per unit area m' of actual floating slabs (as built in laboratory), the resonance frequency of the floating floor f_0 is determined, on the basis of relation (3). The mass per unit area of each floating slabs is shown in Table I. In Table II experimental data are shown.

Table II: Experimental data of tested materials

Sample	Measured RFR Resonance frequency f_r /Hz	Dynamic Stiffness s' /MN·m^{-3}	Airflow resistivity /kPa·s·m^{-2}	Total loss factor η /-	Resonance frequency of floating floor f_0 /Hz
1	66.5	35.0	< 10	0.23	107.2
2	82.9	54.4	< 10	0.12	118.0
3	151.0	180.4	> 100	0.16	220.5
4	136.2	146.7	> 100	0.02	189.0
5	77.0	46.9	-	0.11	141.4
6	89.9	63.9	-	0.08	136.0

4. Experimental results and constitutive model

Experimental data of improvement of impact sound insulation are compared with data of insulation effectiveness estimated on the basis of transmissibility constitutive model, relation (9), since the floating slabs, realized in laboratory, are resonantly reacting. Besides, also Cremer-Vér model implementation, relation (3), is shown. Input data used for calculation are shown in Table II. Comparisons are shown in the graphs of the Figures below:

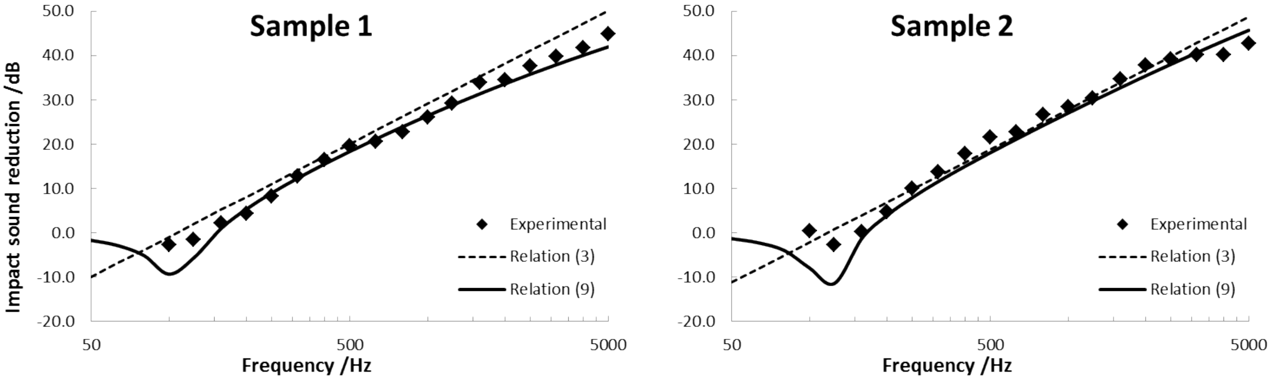

Figure 8: Improvement of impact sound insulations of floating floors with fibrous materials.

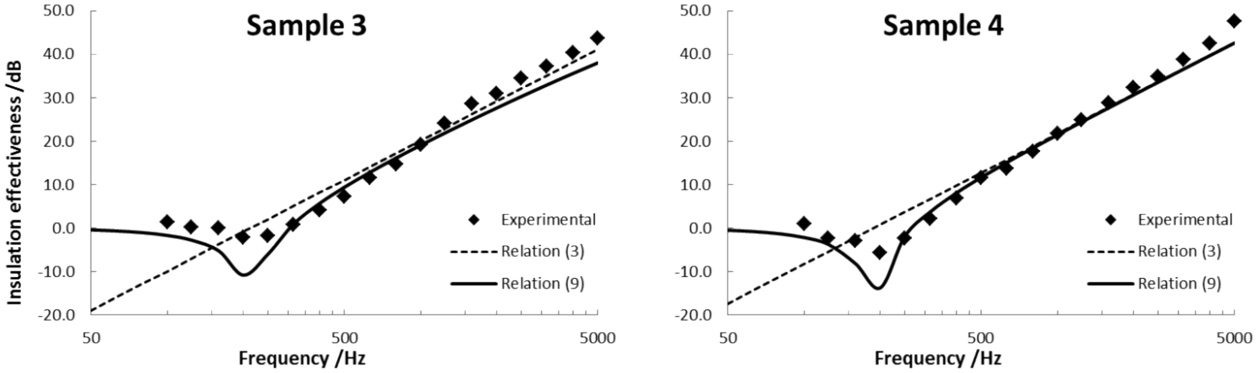

Figure 9: Improvement of impact sound insulations of floating floors with grains materials.

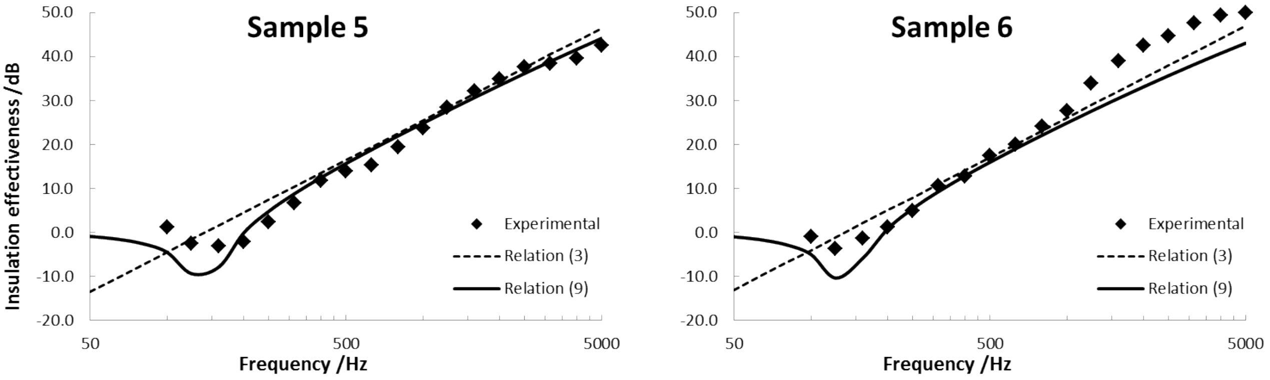

Figure 10: Improvement of impact sound insulations of floating floors with elastomeric materials.

As depicted in the graphs of Figure 8 – 10, transmissibility model allows to estimate the improvement of impact sound insulation, as well as Cremer-Vér model, for frequency above the resonance frequency of the floating floors. Although in terms of accuracy Cremer-Vér model and transmissibility model can be considered as equivalent, at the resonance frequency and in the low frequency range [50-52], the proposed approach, due to the continuity of the transmissibility function, allows to better define the acoustical behavior. Observed deviations, at middle- high-frequencies in experimental data (e.g., samples 3 and 6), mainly depend on the actual mechanical properties of the floating slabs, such as differences in concrete composition, curing behavior, small cracks and occurring possible bridging [53].

4. Conclusions

In this paper a constitutive model for the calculation of the improvement of impact sound insulation of floating floors, is presented. Proposed model, based on input force transmissibility theory, allows to accurately evaluate the actual acoustical behavior of a floating floor, as a function of frequency, by means of a single analytical function.

Theoretical background of transmissibility is applied to the floating floor system, considered as a linear damped single-degree of freedom system. In order to verify the effectiveness of the proposed model, accurate comparisons are performed between experimental data, from laboratory, and estimated data, from mechanical properties of involved materials. Six measurements of improvement of impact sound insulation are carried out in standard laboratory, according to ISO 10140 Standard series, and mechanical properties of resilient materials, used as interlayers, are evaluated from dynamic stiffness, according to ISO 9052-1 Standard, and from damping, according to the *half-power bandwidth method*. As a result, the proposed model can be considered as appropriate in order to estimate the acoustical performance of a floating floor, in terms of insulation, and it is in agreement with the well-known Cremer-Vér model. Moreover, calculated improvement of impact sound insulation, allows to better estimate the impact sound insulation *in situ*, as a function of frequency and for rating evaluation purposes, for several base floors of different building technologies and involved materials.

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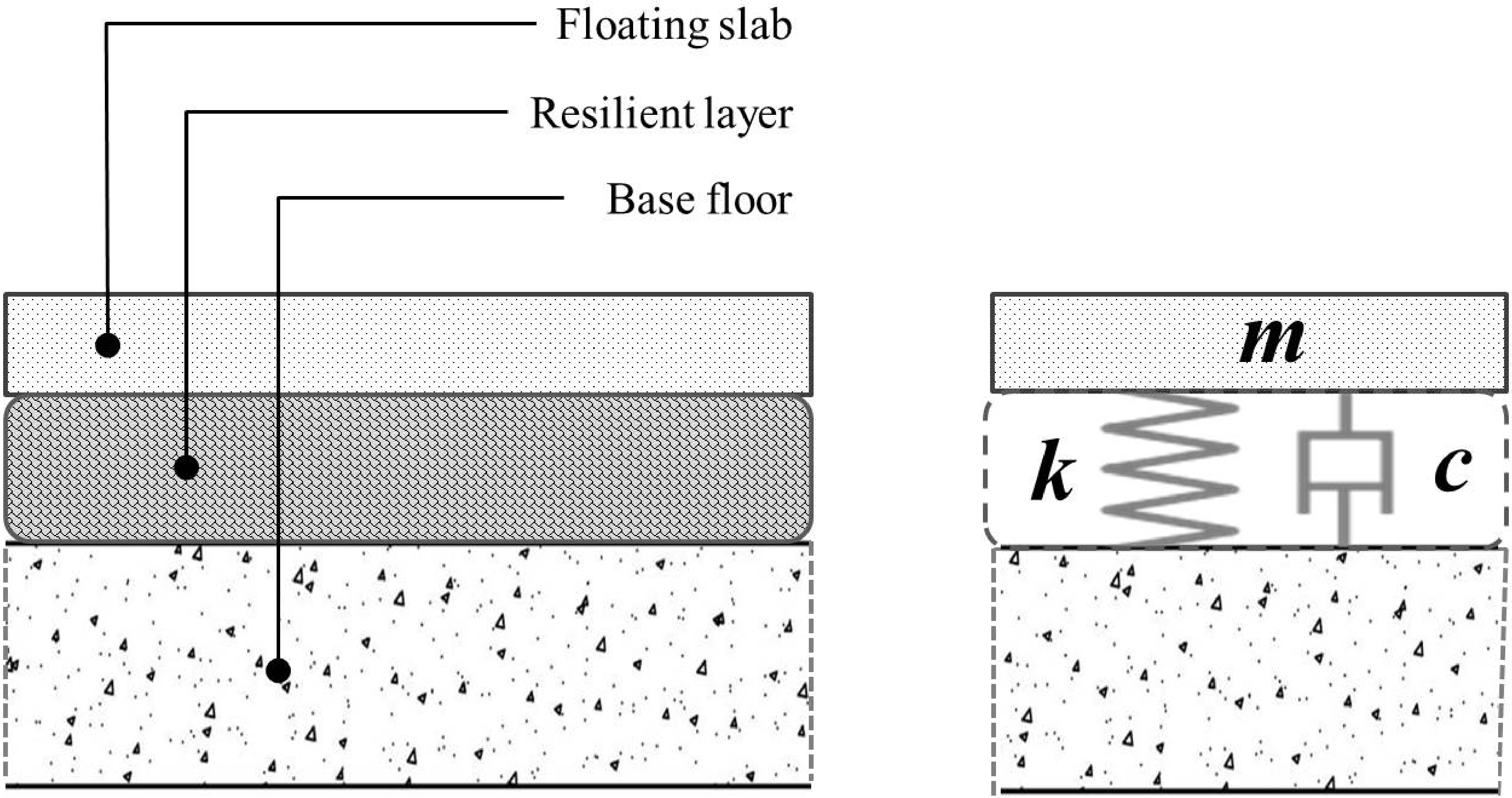
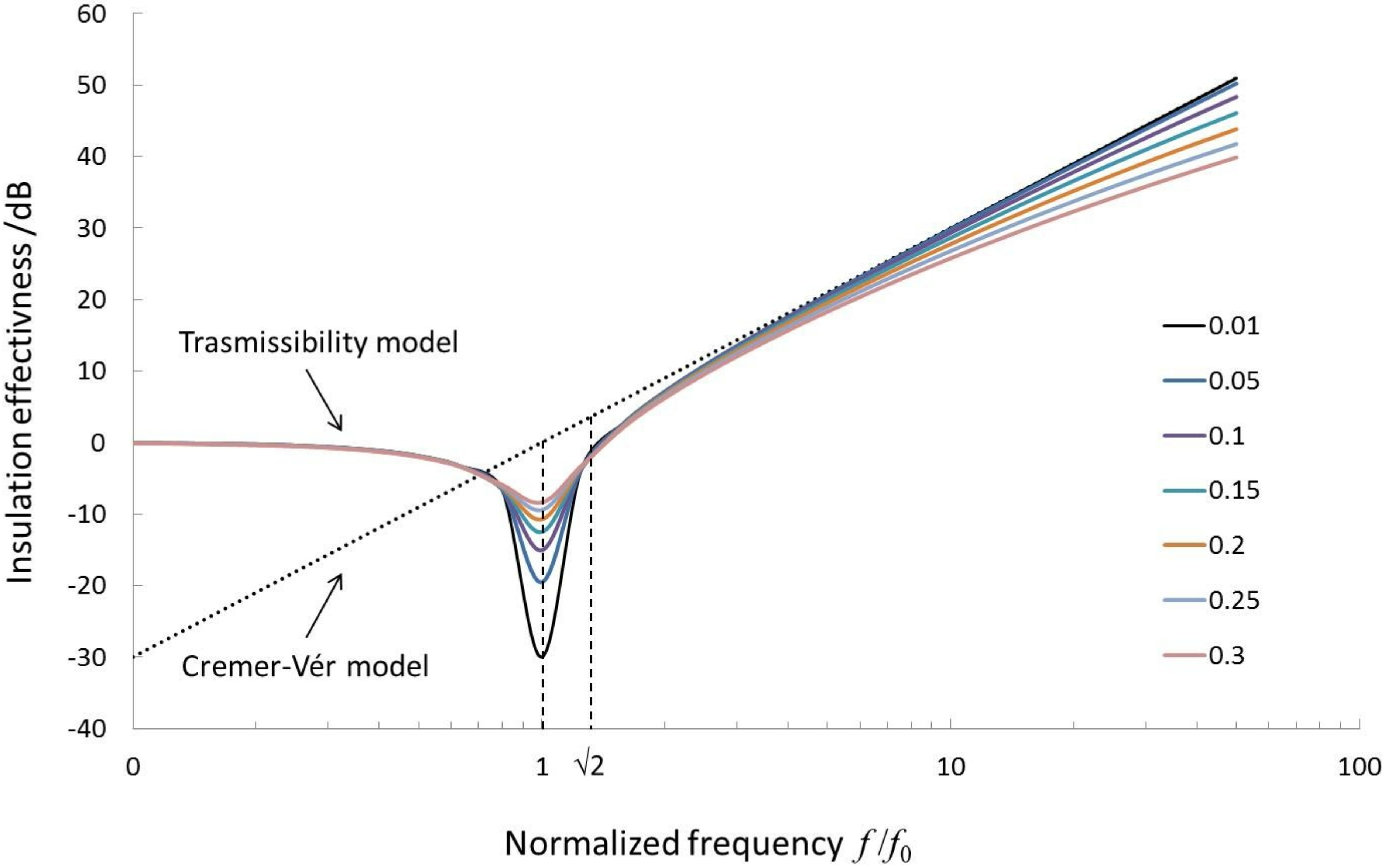
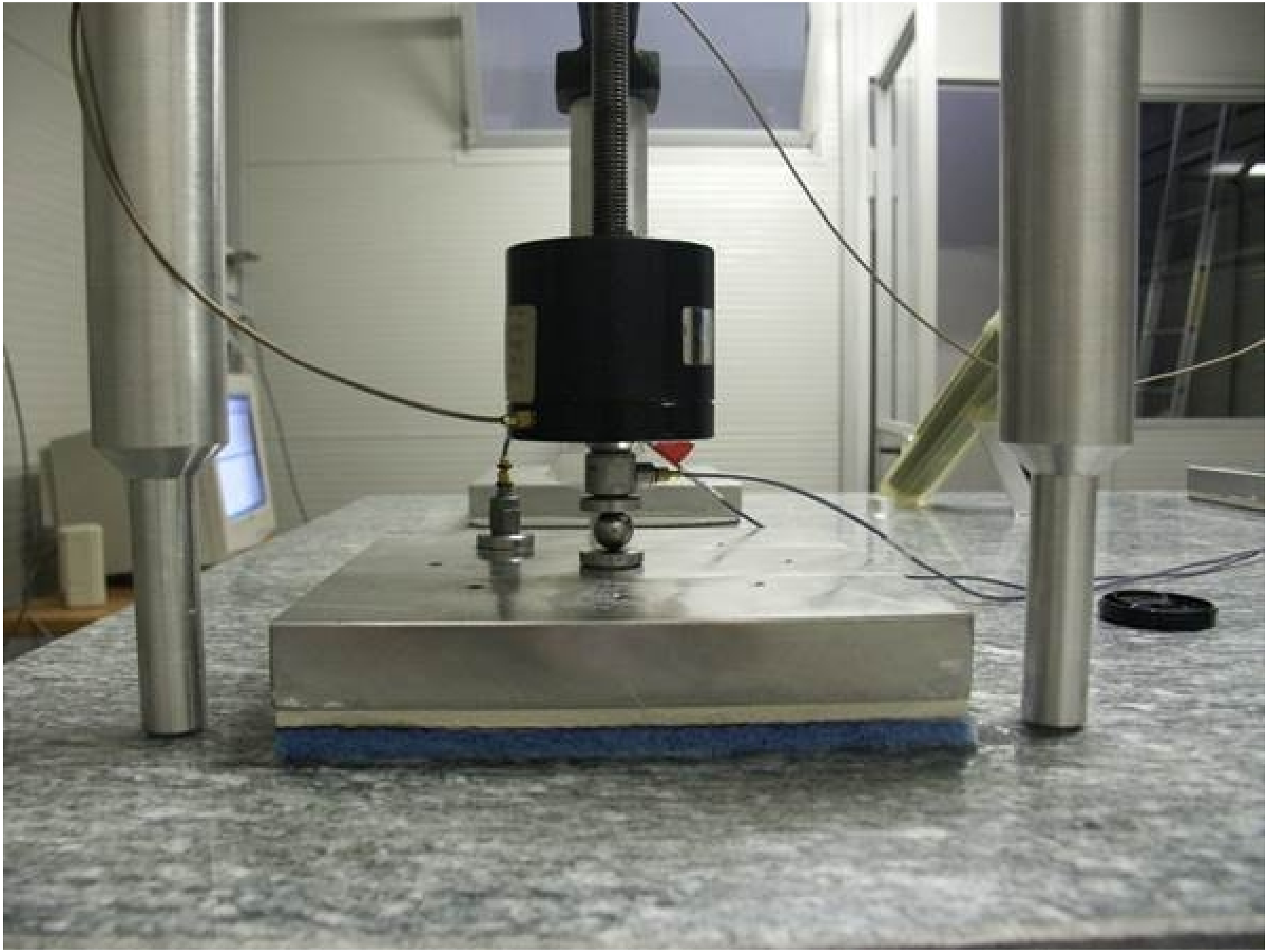
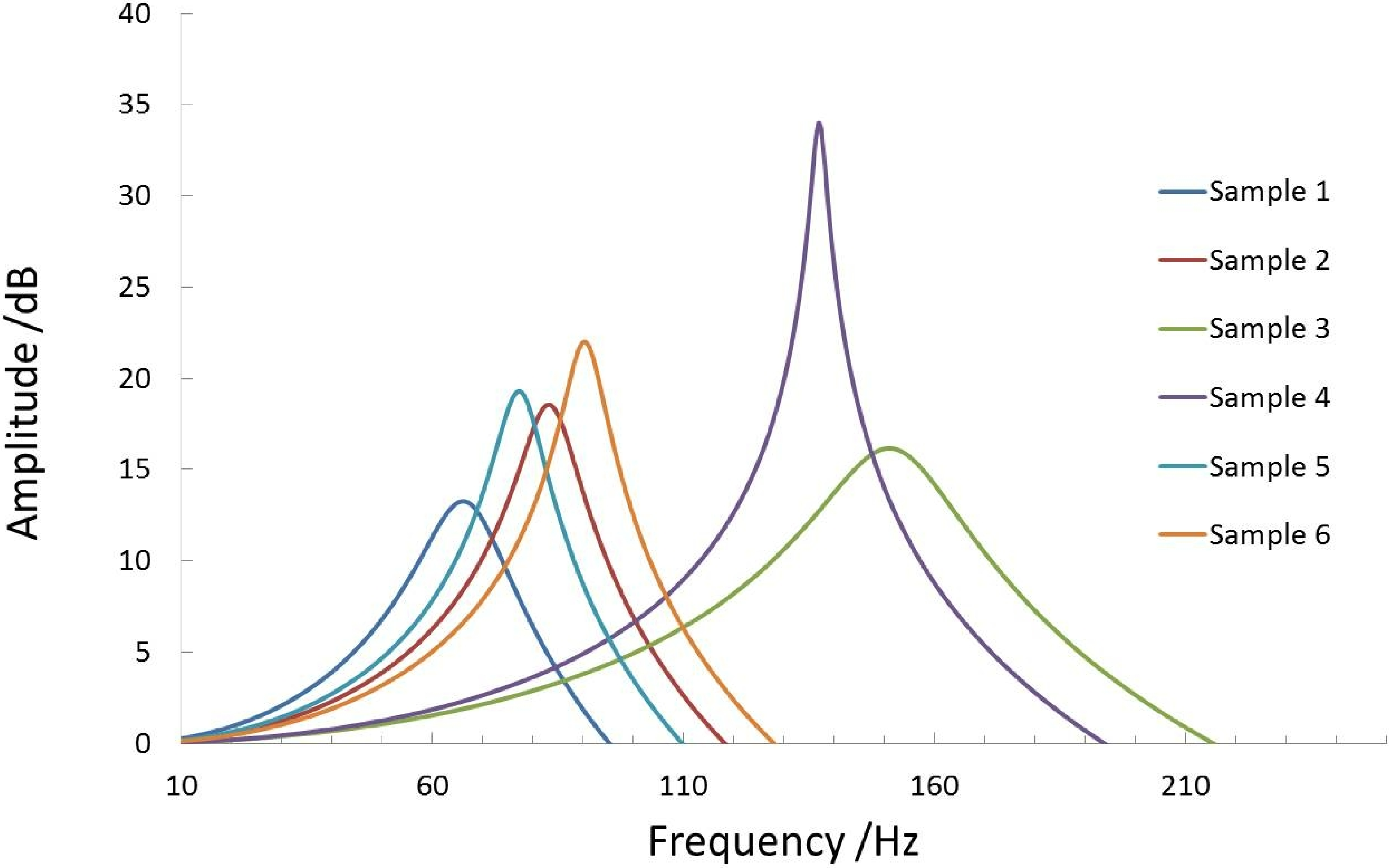
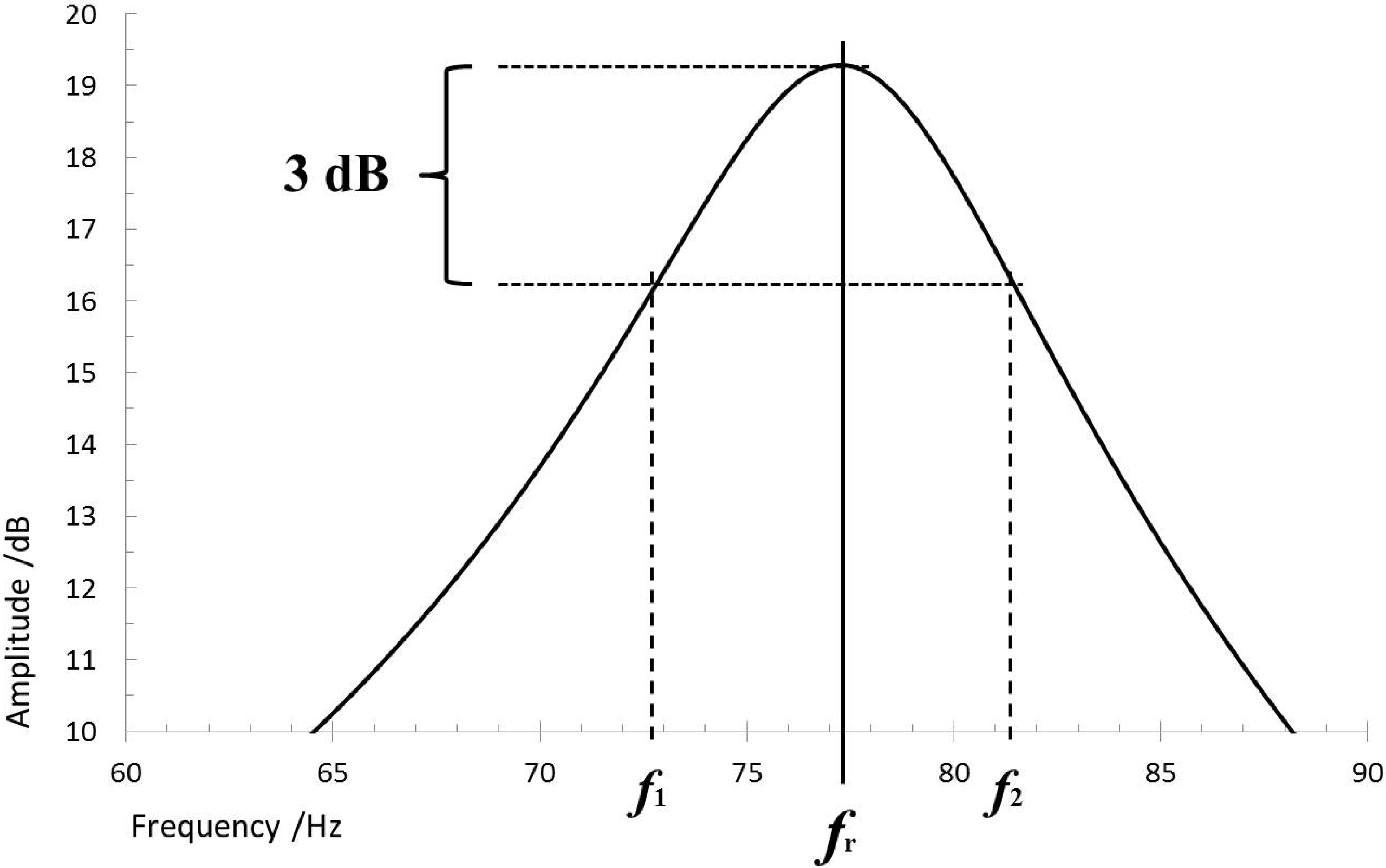

Floating slab
Resilient layer
Base floor
m
k
c

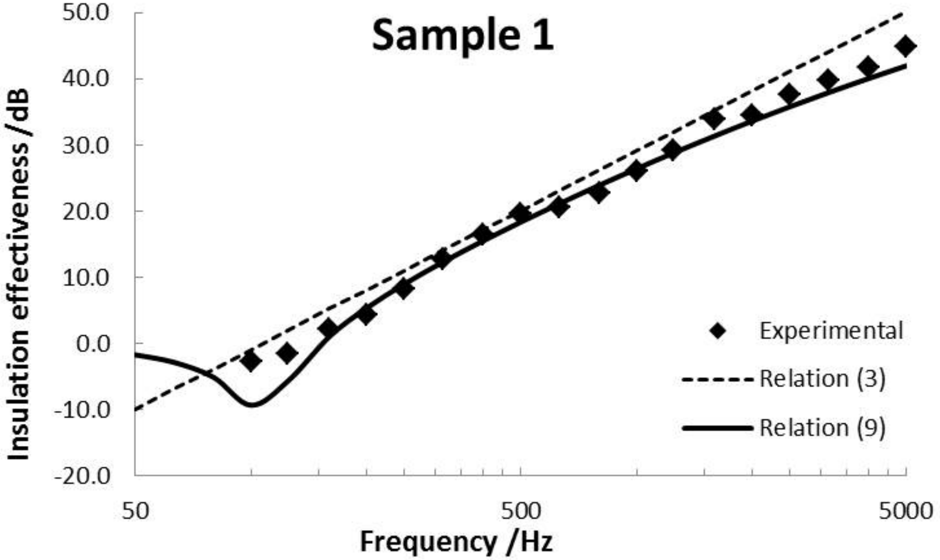

60
50
40
30
20
10
0
-10
-20
-30
-40
Insulation effectivness /dB
Trasmissibility model
Cremer-Vér model
0.01
0.05
0.1
0.15
0.2
0.25
0.3
0
1
√2
10
100
Normalized frequency f/f_0


1
2
3
4
5
6




40
35
30
25
20
15
10
5
0
Amplitude /dB
10
60
110
160
210
Frequency /Hz
Sample 1
Sample 2
Sample 3
Sample 4
Sample 5
Sample 6


3 dB
Amplitude /dB
20
19
18
17
16
15
14
13
12
11
10
Frequency /Hz
60
65
70
75
80
85
90
f_1
f_r
f_2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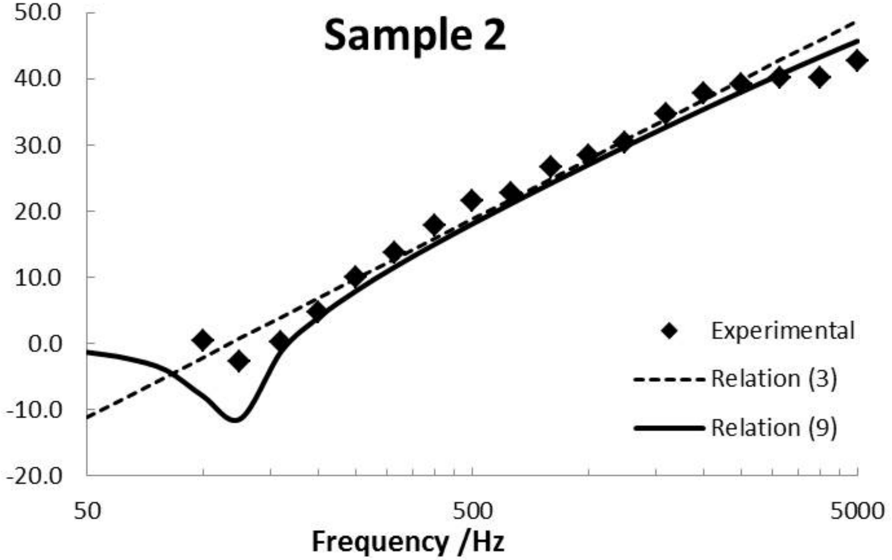
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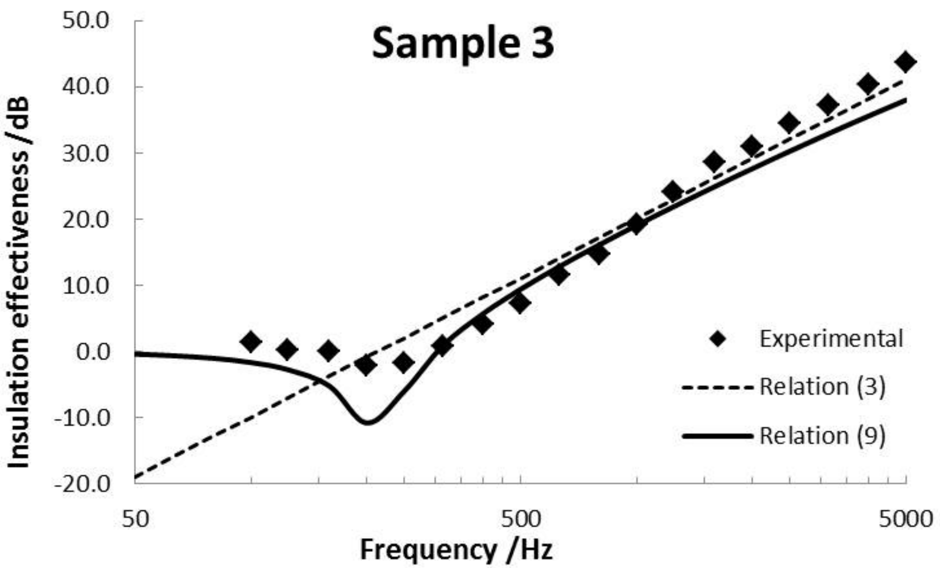
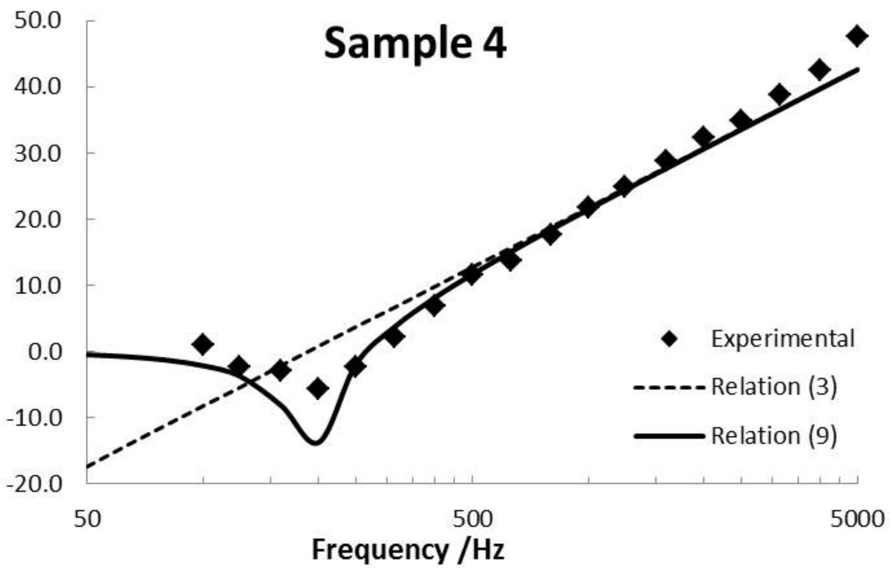
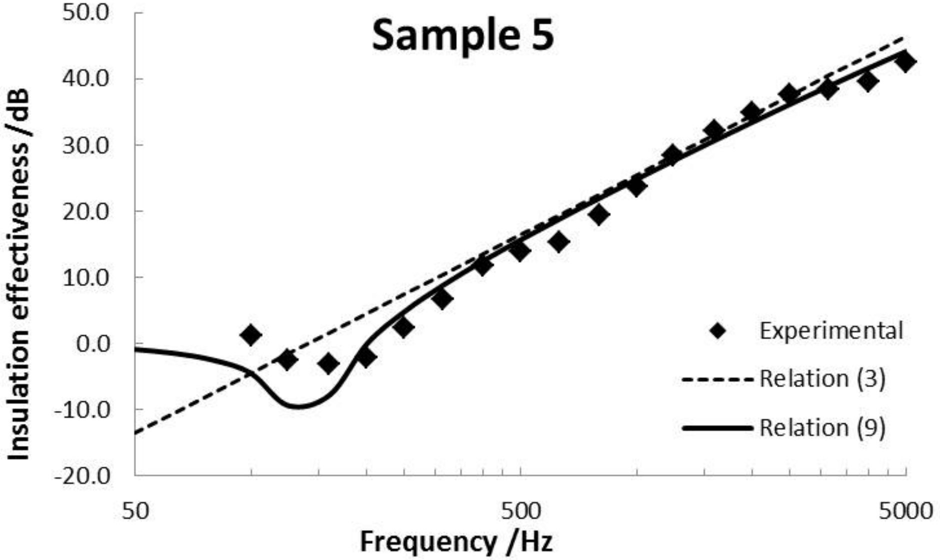
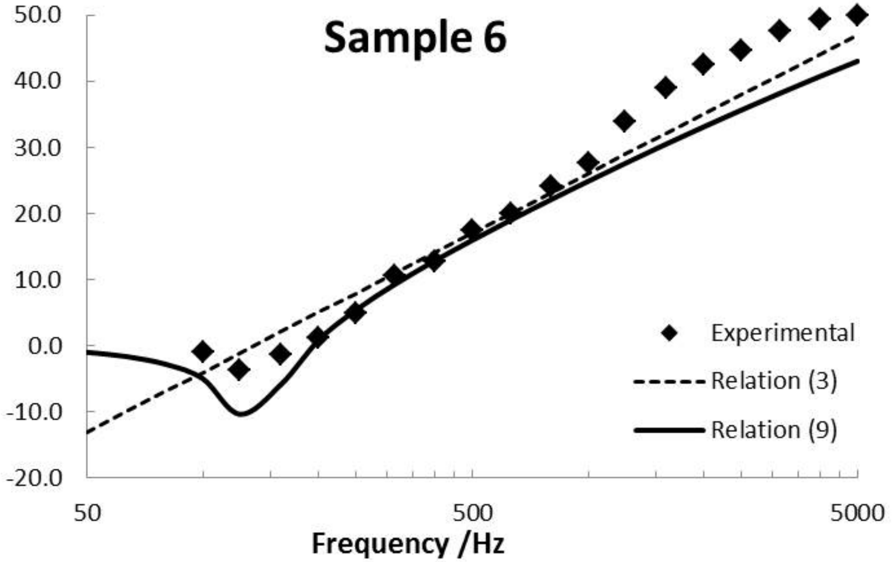

Sample 3
Insulation effectiveness /dB
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
50
500
5000
Frequency /Hz
Experimental
Relation (3)
Relation (9)


Sample 4
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
50
500
5000
Frequency /Hz
Experimental
Relation (3)
Relation (9)


Sample 5
Insulation effectiveness /dB
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
50
500
5000
Frequency /Hz
Experimental
Relation (3)
Relation (9)


Sample 6
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
50
500
5000
Frequency /Hz
Experimental
Relation (3)
Relation (9)