Investigations to determine the dynamic stiffness of elastic insulating materials

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Summary

The dynamic stiffness of elastic insulation materials is an important material parameter in building acoustics and must be known, for example, to predict the resonance frequency of floating floors. The measurement procedure used to determine the dynamic stiffness of elastic layers for floating floors is described in ISO 9052-1. Here, a defined mass is applied to a sample of the elastic layer and from the resonance frequency of this spring-mass system, the dynamic stiffness is determined. With regard to the metrological realization (excitation of the measurement set-up, the arrangement of the sensors and the analysis of the resonance curve), however, the standard leaves many unanswered questions. Also, correction by means of the airflow resistance, as described in the standard, raises questions. Within the scope of a research project to study the physical properties of sustainable insulation materials, an investigation of these questions was conducted at PTB. In the context of the research project, also insulation materials are to be investigated which are used for thermal insulation composite systems (or are planned to be used for these), bringing about a clearly smaller static preload than floating floors. As, in our experience, the dynamic stiffness of insulating materials depends on the static preload, alternatives for the standardized measuring set-up were considered which allow a realistic determination of the dynamic stiffness at a small static load.

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1. Introduction

Acoustic insulating material is used in construction to absorb sound, e.g. in double walls or suspended ceilings or to prevent vibrations from propagation, e.g. underlays under floating floors. In DIN 4109 [1], the German standard on sound insulation, the major property used to describe a materials sound absorption ability is the flow resistivity whereas the dynamic stiffness is the main parameter for the vibrational insulation. These quantities are selected because they can be applied for the prediction of the acoustic properties of buildings. Furthermore, they can be measured with a relatively small effort and are thus well suited to serve as a quality control for acoustic insulation materials.

Within a project on the use of renewables as insulating material in construction, an investigation on the corresponding measurement methods is being performed at PTB. The major aim of the project is to ensure that the applicability of renewables is not limited by special provisions in the measurement methods. In this context, this contribution is dedicated to the measurement of dynamic stiffness.

2. Measurement method

The measurement method for the determination of dynamic stiffness is defined in ISO 9052-1 [2]. Here, a mass representative for typical floating floors is used to impose a static load on a sample of the material to be measured. The mass is excited, and from the resonance frequency f_{res} of this spring-mass system, the dynamic stiffness is calculated. It is mentioned that the mass may be excited by sine shaped forces of less than 1 N, and if there is a dependence of the resonance frequency on the excitation force observed, an extrapolation to a force of 0 N is to be applied.

White noise or impulses may also be applied, but further details are not provided in the standard.
The whole procedure leaves several open questions which have been addressed by other authors in the past. The influence of airflow resistivity on the dynamic stiffness of open cell material was investigated in [3]. In [4], different excitation mechanisms (hammer, sine sweep and white noise) were investigated. It was concluded that the different excitation mechanisms lead to very similar resonance frequencies.
In view of modern measurement techniques our investigation focuses on the question, whether impulse response methods can be used to measure the resonance frequency and how existing nonlinearities influence the measurement results. Furthermore, we assessed which forces should be applied in material testing to reflect the real in-situ conditions.

3. Estimate of forces

To estimate the forces, electromechanical analogies are used. The test set-up (Figure 1) is thus modeled by a force source which acts in parallel on the mass *m* and the spring with the spring konstant *k* (Figure 2). The latter characterizes the elastic properties of the material to be tested. It is simply

$$k = s'A \tag{1}$$

with dynamic stiffness s' and the surface area of the element *A*. When testing is performed, the force is usually measured. This measured force is then the force which really acts on the mass, whether it is produced by a shaker or a hammer.

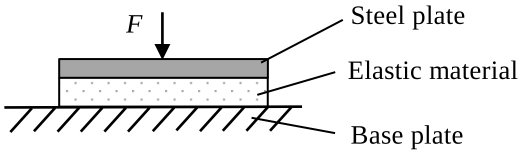


Figure 1. Test set-up

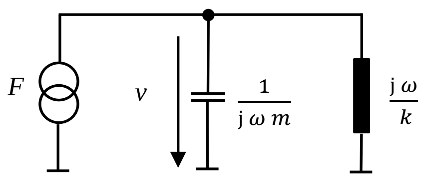


Figure 2. Electromechanical model of the test setup

The ratio between velocity *v* and force *F* directly follows

$$\frac{v}{F} = \frac{\mathrm{j}\,\omega\,/k}{1-\omega^2\,m/k} \tag{2}$$

Losses are neglected in the simple model used here but they can easily be included, e.g. by introducing a complex spring constant *k*.
In reality, people are walking on a floating floor (Figure 3) or a tapping machine excites the floating floor. This situation is modeled by a blocked force of the source F_S, a source mobility Y_S, the mobility of the floating floor Y_{ff} and the spring (Figure 4). The ratio between velocity *v* and force F_S is then

$$\frac{v}{F_S} = \frac{\mathrm{j}\,\omega\,Y_S\,Y_{ff}/k}{Y_S\,Y_{ff}+\mathrm{j}\,\omega\,\left(Y_S+Y_{ff}\right)/k} \tag{3}$$

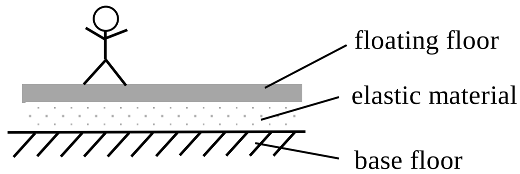


Figure 3. In-situ conditions

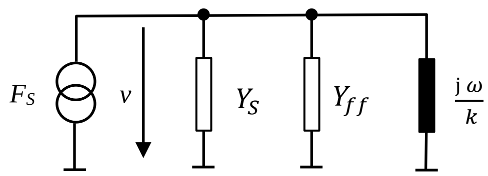


Figure 4. Electromechanical model for in-situ conditions

To have a realistic excitation in the test set-up, it is necessary that the velocity in Figure 2 is in the same order as the velocity in Figure 4. The force in the test set-up is therefore expressed as

$$F = F_S \frac{1-\omega^2 m/k}{\sqrt{\left(\frac{\omega}{k}\,\frac{Y_S+Y_{ff}}{Y_S\,Y_{ff}}\right)^2+1}} \tag{4}$$

Source data for walking persons and tapping machines are available from [5], [6] and [7]. The mobility of the floating floor is estimated from the point mobility of an infinitely large concrete element of thicknesses between 35 and 60 mm. For impact durations between 0.01 and 0.1 s a force between 1 and 30 N is estimated for walking persons. For tapping machines, the force is in a range between 150 and 1000 N.

4. Measurements

To investigate some of the questions mentioned above, a series of measurements have been performed. The test objects included elastic layers manufactured from soft and hard foams (PU, EPS and XPS), mineral wools and coconut fiber. For all measurements a concrete slab with a mass of 400 kg was used as a base plate. The slab is resiliently mounted on a steel rack with a resonance frequency of approx. 12 Hz. An accelerometer, which was mounted as close to the center of the steel plate as possible was used to detect the desired input signal. An alternative set-up with four accelerometers mounted on the corners of the steel plate was also used. This allowed us to gather more detailed information about the vibration behavior of the plate. For impulse excitation, a modal hammer with interchangeable tips (rubber, plastic or steel) was employed. A shaker was used for sinus sweep excitation. In a first approach, the shaker was attached to a specially designed structure, which in turn stood on the concrete slab with elastic layers used to provide mechanical decoupling. However, first tests showed that nevertheless the vibrations of the supporting structure interfered with the test set-up, providing unsatisfying results. To eliminate the problem, the shaker and its supporting structure were then mounted on a manually operated hydraulic lifter, as shown in Figure 5. Highly versatile data acquisition software together with an 8-channel measurement frontend was used to perform the measurements and subsequent signal processing.

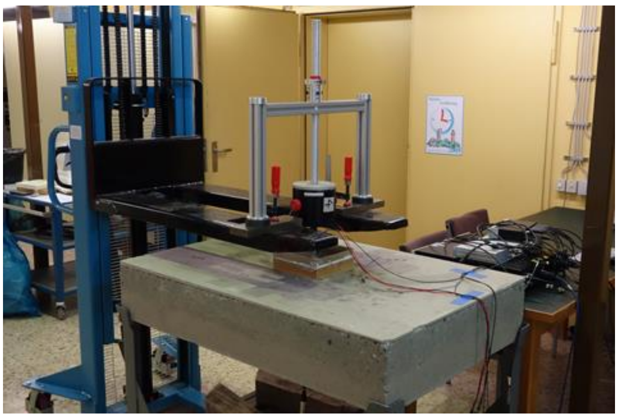


Figure 5. Measurement setup with shaker and supporting structure mounted on a hydraulic lifter

4.1. Remarks on sweep excitation

Before the advent of FFT analyzers, a well-established approach for the measurement of resonance curves consisted of a level recorder and a mechanically synchronized sine oscillator. Special recording paper with a calibrated frequency scale was used instead of the more common time scale. This approach worked under the assumption that the level of the time signal has its maximum value at the resonance frequency of the observed system. Any real system has a certain group delay, which causes the time signal to “lag behind” the resonance frequency, which means that the maximum level of the time signal appears at a higher frequency than the resonance frequency. The difference depends on the rate at which the frequency travels. A test measurement with a logarithmic sweep signal of different lengths, but with a constant frequency range (10 Hz to 500 Hz) and sampling rate (32 kHz) was performed to evaluate this effect. The resonance frequency was determined in the time domain, as described above, and in frequency domain using FFT analysis. Soft mineral wool with a thickness of 40 mm was used as a test object. The results are shown in Figure 6.

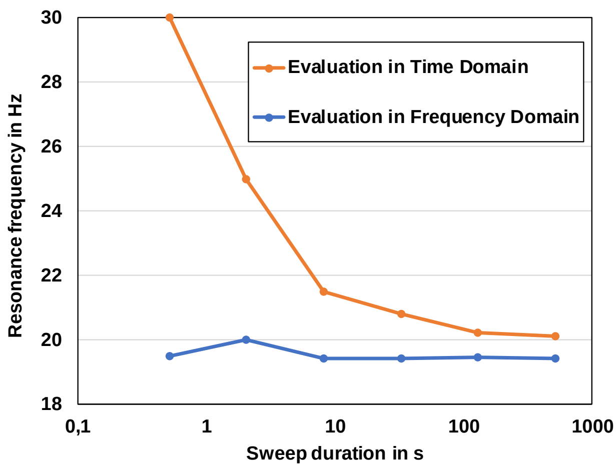


Figure 6. Resonance frequency f_{res} measured with different sweep durations and evaluated in the time and in the frequency domain

Evaluation in the frequency domain delivers a more or less steady result; the deviations at short sweep durations can be attributed to poor frequency resolution. In time domain, the detected resonance frequency approximates the actual value, but only if very long sweep durations are used, which represent a quasi-stationary excitation. It is hence strongly recommended to use FFT analysis in order to obtain correct measurement results.

4.2. Hammer vs. sweep excitation and considerations on linearity

It is often desireable to perform tests on structural vibration by means of hammer excitation. While the attachment of a shaker is elaborate and time consuming (see Figure 5), a hammer measurement is quickly applied and delivers reliable results. Then again, the influence of the different force applied to the test object has to be taken into consideration. As the dependence of the measurement result on different excitation forces is a general issue, some test objects were measured using both hammer and shaker excitation, with the excitation forces varied over a wide range, from the lowest to the highest excitation forces that the deployed equipment was capable to deliver. The results are displayed in the following figures. It must be pointed out that all results show the apparent dynamical stiffness s'_t. The parameter s'_a, which takes into account the dynamic stiffnes of the enclosed air, is not included. The reason for this will be discussed below.

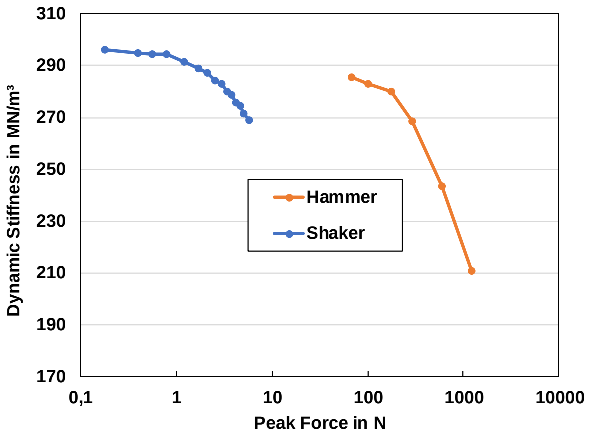


Figure 7. Apparent dynamic stiffness s'_t obtained using hammer and shaker excitation of 30 mm XPS foam

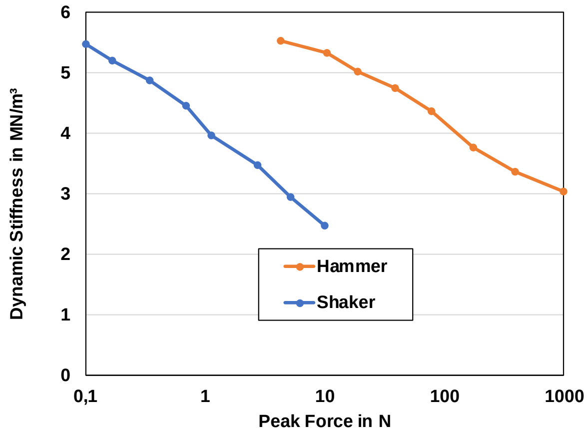


Figure 8. Apparent dynamic stiffness s'_t obtained using hammer and shaker excitation of type 3 40 mm mineral wool

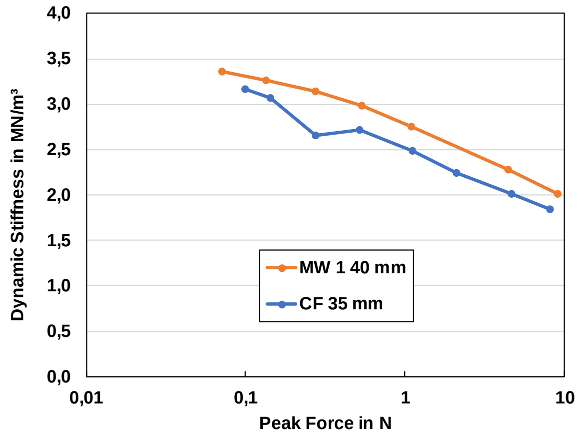


Figure 9. Apparent dynamic stiffness s'_t of type 1 40 mm mineral wool and 35 mm coconut fiber, obtained using shaker excitation

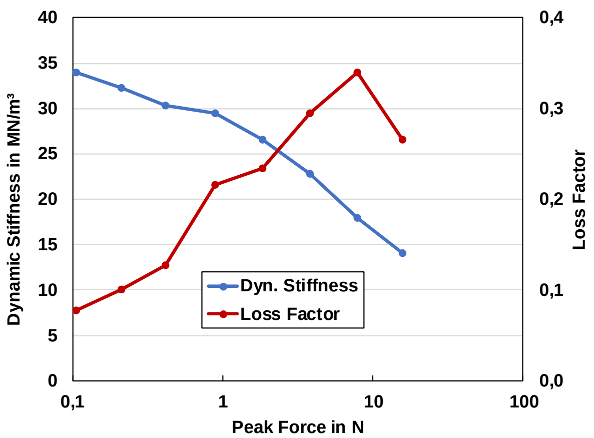


Figure 10. Apparent dynamic stiffness s'_t and loss factor, type 2 40 mm mineral wool, obtained using shaker excitation

The samples clearly show a dependency of the dynamic stiffness related to the excitation force. The resonance frequency and thus the dynamic stiffness decrease with growing force. All fibrous materials display very similar behavior. For a logarithmic force axis, the resulting graph is close to a straight line with negative slope. As shown in Figure 10, the loss factor η, which is derived from

$$\eta = \frac{\Delta f_{3\mathrm{dB}}}{f_{\mathrm{res}}}, \quad (5)$$

has a linear relation to log(F) with a positive slope. The XPS foam displays a different behavior; the corresponding graph is linear for a linear force axis (not shown here). Hammer and shaker excitation both seem to deliver comparable results. Of course, the peak force of a hammer blow is not comparable to that of a sinusoidal excitation force. As the dynamic stiffness is dependent on the excitation force, it should be discussed which force delivers a representative result for the dynamic stiffness. For sinusoidal excitation, the measurement standard requires the use of excitation forces in a range of 0.1 N to 0.4 N for elastic layers with a dynamical stiffness lower than 50 MN/m³, which is the case for all fibrous materials tested in this study. Unfortunately, the standard does not specify whether these values refer to peak or rms force. The final value for the resonance frequency is then obtained by an extrapolation of the results to an excitation force of 0 N. This approach is challenged by several aspects covered in this report. First, the relation between force and resonance frequency is not necessarily linear, which can be shown for instance if a linear force scale is used for type 3 mineral wool:

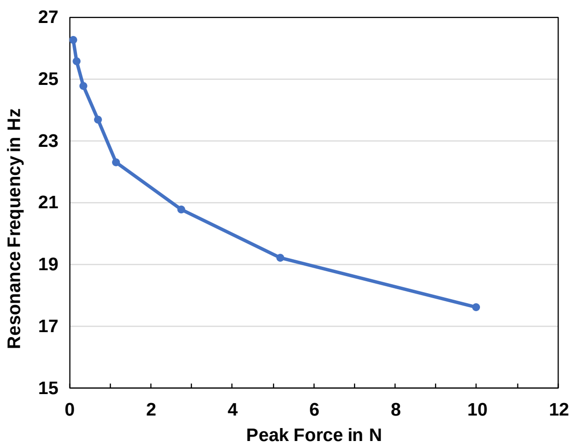


Figure 11. Resonance frequency, type 3 40 mm mineral wool, obtained using shaker excitation

Second, the considerations about the realistic impact forces of human walkers given previously in this publication also support the assumption that an extrapolation to an excitation force of 0 N will not produce feasible results. In a first approach, the authors recommend using a 1 N peak for sinusoidal excitation, which could be compared to a 100 N peak of a hammer impact, but here the influence of different hammer tips should be considered. In this research, a plastic tip was used for the XPS foam and a rubber tip was chosen for the type 3 mineral wool.

4.3. Signal processing

In theory, the excitation force must be kept constant for all frequencies to obtain a proper resonance curve. With hammer excitation it is quite easy to achieve this goal, as a flat force spectrum is produced over a wide frequency range, which may be controlled by varying the mass and tip stiffness of the hammer. This is not the case with shaker excitation, as there are numerous interactions between the shaker, the test object and the supporting structure. As the force delivered by the shaker depends primarily on the current fed into it, some improvement is achieved by using an amplifier which can be operated as a voltage controlled current source. But even this way a flat force spectrum cannot be obtained, as Figure 12 clearly shows. However, with signal processing in the frequency domain it is possible to apply a correction by performing a complex division of the measured acceleration spectrum by the measured force spectrum. The resulting resonance curve has a different and most likely more reasonable shape. As this feature should be available with most measurement systems, the application of this correction is recommended.

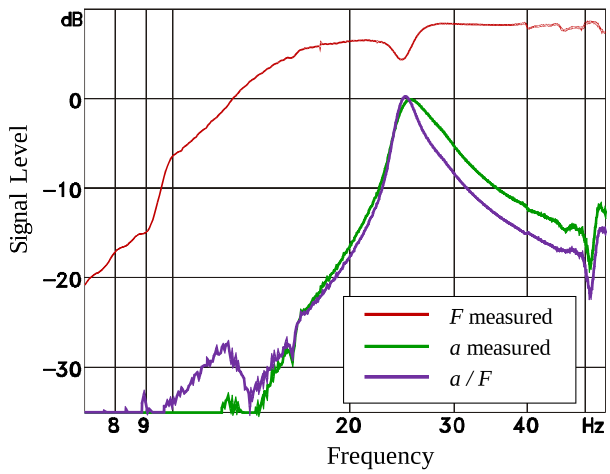


Figure 12. Example of measured force and acceleration spectrum and the corrected acceleration spectrum

4.4. Preparation of the plaster layer

As most specimens do not have a plane surface, a leveling layer is mandatory to achieve a proper coupling between the steel plate and the test specimen. Here, the standard prescribes a plaster layer of at least 5 mm thickness. To prevent the plaster from infiltration into the specimen, a thin plastic foil is placed on the test object first. Figure 13 shows a typical example of a prepared specimen.

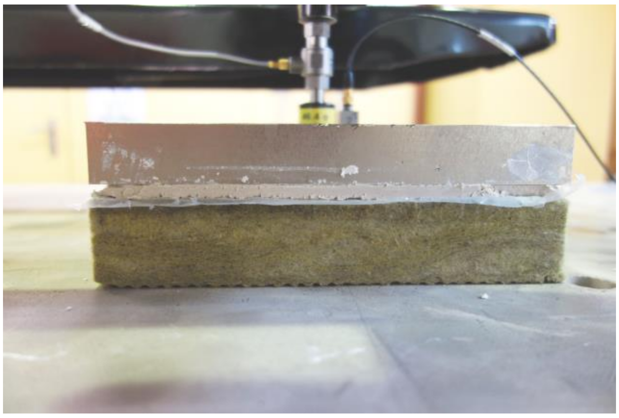


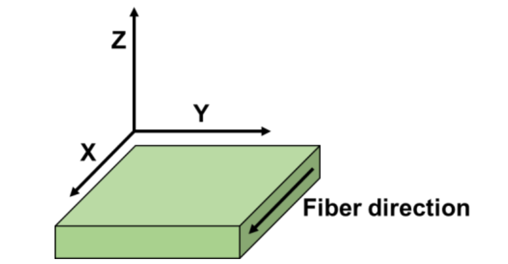
Figure 13. Prepared sample with plastic foil, plaster layer and steel plate

In practice, it is not always easy to produce the required thickness of 5 mm. The standard demands a plaster of "low viscosity" without giving further hints on how it has to be prepared. If the plaster is too stiff, there will probably be too many bubbles left if the steelplate is embedded on the plaster layer. If it is too runny, most of it will be squeezed out on the perimeters, producing only a thin layer of plaster. In the course of the presented study, sometimes no more than 3 mm thicknesses were achieved, but there was no apparent influence on the measurement results. It should be considered that freshly prepared plaster contains a substantial amount of excess water, which will evaporate very slowly as long as the plaster is covered by the steel plate. As the mass of the plaster contributes to the overall mass load of the set-up, it is recommended to determine its mass immediately after the measurement is performed.

4.5. Significance of airflow resistivity

For a lateral airflow resistivity in the range from 10 kPa s/m² to 100 kPa s/m², a correction term s'_a is required to take into account the dynamic stiffness of the gas enclosed in the specimen. However, the airflow resistivity of common fibrous materials like mineral wool, etc. is usually only measured in the vertical direction, also because the established test apparatuses are not suited for in-plane measurements. As the surface layers of these materials do often have a higher density than the core, the airflow resistance for lateral flow are expected to be significantly smaller than for vertical flow. A test apparatus was designed at PTB which renders a possibility to measure the airflow resistance in both the lateral and vertical directions. Table I shows a typical result for a sample with a measured apparent dynamic stiffness of about 3,9 MN/m³ (F_{peak} = 1 N).

Table I. Airflow resistivity of a mineral wool sample for different meausurement directions



r (X)	r (Y)	r (Z)
7 kPa s/m²	7 kPa s/m²	15 kPa s/m²

In the vertical direction (Z), the airflow resistivity is in a range that requires the application of s'_a (2,8 MN/m³ in this case), whereas the lower airflow resistivities in lateral directions (X and Z) would indicate that ISO 9052-1 is not applicable for this material, because s'_a is in the same range as s'_t. This applies for many common insulation materials, which is quite unsatisfactory and should be discussed.

An alternative measurement set-up is devised in [3]. Here, the sample is surrounded by 1 m² of the same material. This extension is covered with a chipboard panel, thus emulating the airflow into a larger sample area instead of using the correction s'_a. There is a small gap around the original set-up for mechanical de-coupling. Whether or not this approach better reflects the in-situ conditions of a real floating floor must be discussed. The correction s'_a is based on the assumption that the air volume in the sample is surrounded by an airtight enclosure, which is also more or less the case with real floating floors. If the top of the floor moves as a rigid plate when excited by, for instance, a human walker, s'_a is also valid for in-situ conditions. This will not be the case if the top of the floor is deformed only in the area of the impact. Further research on this topic is necessary.

5. Conclusions

Several aspects of the determination of the dynamic stiffness as described in ISO 9052-1 have been examined in the run-up of an upcoming research project. Foams and fibrous materials were tested with the measurement set-up described in the standard. It turned out that evaluation of the resonance frequency in the time domain is not feasible, so an evaluation in the frequency domain is recommended. When using sweep excitation, a complex compensation of the measured force spectrum in the frequency domain will increase the accuracy of the resonance curve. All tested materials show a dependency of the dynamic stiffness with respect to the excitation force in the way that the stiffness decreases with growing force. A sample of coconut fiber revealed the same characteristics as those made of mineral wool. The measurement results and theoretical considerations on the impact force to be expected in situ lead to the conclusion that an extrapolation to a force of 0 N will probably not produce realistic figures. A first suggestion is given for a more expedient input force. Hammer excitation is also feasible, but it is difficult to relate the impact force to sinusoidal excitation. For application of the correction term s'_a it is essential to use the airflow resistance measured in lateral direction, which unfortunately creates an unsatisfactory situation in numerous cases.

6. Future research

The measurement set-up as described in the standard emulates a static load of 200 kg/m², which is realistic for floating floors. This is different for test specimens that are designed to be used in thermal insulation composite systems with nearly no static load and only a small amount of dynamic load. One suggestion for a feasible measurement set-up is to mount a base plate of about 20-30 kg on a strong and heavy shaker. Instead of the steel plate a lightweight (300 grams) but stiff top plate must be employed. The excitation force will then be generated only by the inertia of the top plate. Figure 14 shows a sketch of the measurement set-up. In order to check the validity of the correction term s'_a, further research and discussion is essential.

Acknowledgements

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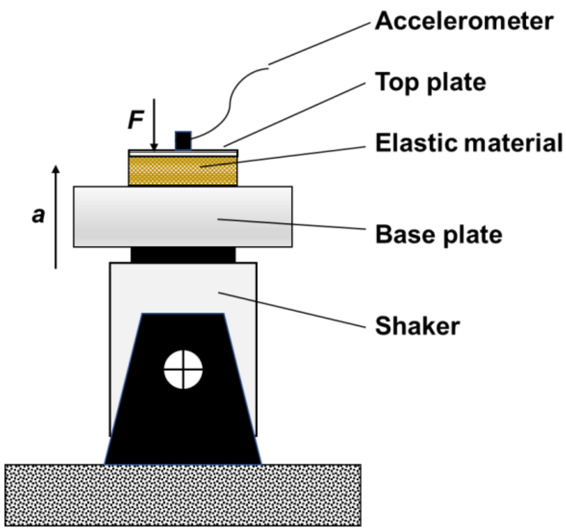

Figure 14. Suggested set-up for measurements with small static loads

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