Vibration reduction in automotive applications based on the damping effect of granular material

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Introduction

The improvement in sound quality is an important aspect in the development of automobiles, as it influences the customers comfort and therefore the purchase decision. Furthermore, the legislature has passed several bills that aim at tightening the sound radiation threshold within the next decade. In order to improve the sound emission properties of lightweight designs, extensive research efforts have been devoted to develop sophisticated concepts that achieve an excellent noise reduction at a low mass. A thermo-acoustical encapsulation is a very promising passive approach to significantly reduce the noise radiation. In [1] an encapsulation made of foamed material applied to an engine is investigated. Often encapsulations are designed as a spring-mass-system and therefore they consist of a bimaterial system. Another passive concept is studied by Hering [2], where a structural intensity analyis computes the best position to add a small mass in order to reduce the resulting vibrations. In addition, a sound reduction can be achieved by modifying the geometry, e.g. by applying stiffening elements on the surface of the structure [3]. It is important to note that not only the sound level but also the human perception of the sound radiation is an important factor that needs to be taken into account. Therefore, psychoacoustic investigations need to be carried as was done in Duvigneau et al. [4]. Here, a numerical approach, which can be used to assess the quality of the sound radiation of an engine with respect to its psychoacoustic characteristics, has been developed. Therefore, a holistic numerical simulation is executed to predict the sound that is in a second step rated by test persons in a hearing test. In this way, the psychoacoustic design can be improved at an early stage of development process.

This study presents a passive lightweight concept using granular materials, with the aim to achieve both a lower sound emission level and a reduced mass compared to the original configuration. This concept was introduced in a previous paper by the authors [5], where the excellent damping properties of granular materials was demonstrated. In their study they focused on automotive applications and used an oil pan to show the performance of novel approach. Since the granular material needs to store in the bottom plate of the oil pan a new design was developed. As the main result of the conducted study a lightweight concept was proposed, which offers both a reduced mass and a lower amplitude of the sound pressure. Moreover, the influence of the position of the granular material on the vibrations was analyzed. The position of the granular filling cannot be controlled, if only one large cavity and a partial filling are used. For this reason, the effect of the distribution of partial fillings was investigated in detail by Koch et al. [6] in follow-up article. In this publication, a combination of honeycomb structures with granular materials was proposed. Sandwich panels with a honeycomb core layer offer excellent stiffness to weight ratios while granular materials provide the required damping properties. The honeycomb structure allows a defined positioning of the granules, which is necessary to investigate the influence of the filling distribution on the damping properties of the novel concept. Furthermore, different types of sand as granular material were tested. The presented concept was lighter compared to the original oil pan and achieves a significant reduction in vibration amplitudes. The paper at hand continues the previous work of Duvigneau et al. [5] and Koch et al. [6]. Therefore, three new and important aspects are examined in this study. First, different filling materials are examined and compared with the most effective sand type of the previous studies. Second, it is investigated whether selected modes can be suppressed by an adapted positioning of the granular material. Finally, it is examined how the vibration behavior differs in a horizontal and a vertical suspension.

Experimental setup

The vibration behavior of the oil pan bottom and the honeycomb sandwich structure is measured with the help of a laser scanning vibrometer (model PSV-400 from Polytech). The vibrometer uses the Doppler Effect, which allows a contactless measurement of the surface velocity. The measuring object is suspended with cords. Consequently, free-free boundary conditions are realized. The excitation is realized with an electro-dynamic shaker (Mini Shaker Type 4810, Brühl & Kjær). The initiated forces are measured with a force sensor. In order to be able to compare the results, the excitation point and the number of measuring points are kept constant. The experimental setup is shown in Fig. 1. Both, the frequency response and the root means square (RMS) value of the vibration are used to show the influence of the granular material. The RMS amplitude of one mesuring point is determined by the amplitude x_i at the frequency i and the number of used frequencies n by

$$x_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2}. \quad (1)$$

The design of the original oil pan, which is shown in Fig. 2, has been adapted. While the upper part remains unchanged, the lower part is replaced by a new construction with one or more cavities, which can be filled with different granular materials. Both the original oil pan and the new constructed oil pan bottom are made of aluminum. If not stated otherwise, we deploy sand as the granular filling material, which has several beneficial properties such that it is environmentally friendly, cheap, recyclable and easy to handle. 95 % of the sand particle have a grain size between 0.1 mm and 0.48 mm. The average grain size is 0.3 mm and the maximum grain size is 2.6 mm.

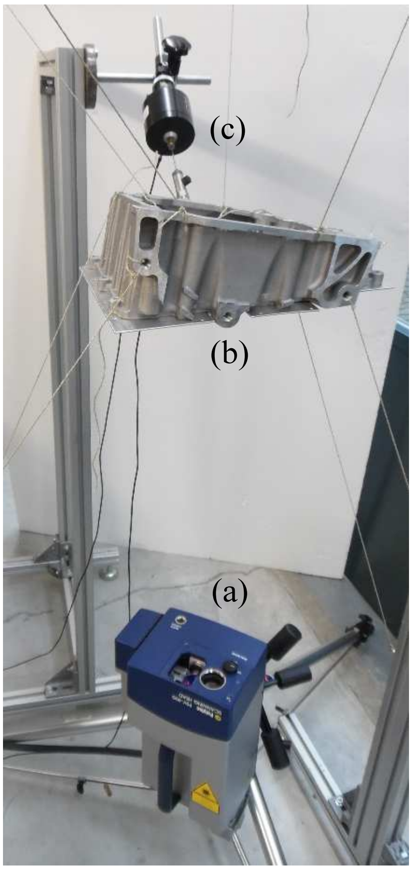

Fig. 1: Experimental setup with (a) Laser scanning vibrometer, (b) Oil pan, (c) Shaker.

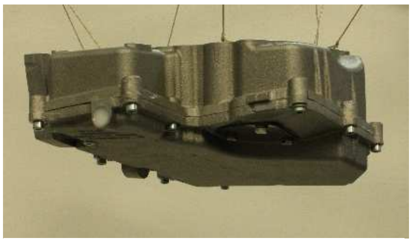

Fig. 2: Oil pan with original bottom.

Vibrational behavior of a one cavity oil pan

Fig. 3: Design of the oil pan bottom prototype I, with one large cavity for granular material.

This section gives an overview about the first steps of the basic concept that was introduced by Duvigneau et al. [5], wherein a lightweight-damping concept is presented, which uses sand as a granular material in one large cavity. Fig. 3 shows the developed oil pan bottom configuration that is in the following referred to as prototype I. The individual components are connected via bolts. The new bottom weighs 1994 g and has a capacity of 760 g with respect to the chosen type of sand. The original bottom is significantly lighter than the prototype I as it only weighs 1095 g. The frequency responses of the original oil pan, the empty and fully filled prototype I are shown in Fig. 4. It is easy to observe that the filled version of prototype I has significant lower amplitudes than the original bottom and the empty prototype bottom. However, the presented concept is 2.5 times heavier than the original configuration and thus no longer attractive for real applications. Therefore, the thickness of the oil pan bottom was significantly reduced from 4 to 1 mm and consequently a drastic reduction in mass to 553 g was realized. In this lightweight design also the height of the spacers has been reduced from 11 to 5 mm and consequently the capacity is also decreased to 347 g of sand. Thus, the fully filled lightweight concept is 195 g lighter than the original version. The frequency response of the original bottom as well as the filled and unfilled lightweight concept are given in Fig. 5. The lightweight concept shows lower vibration amplitudes than both the original bottom and the empty lightweight bottom. Table 1 summarizes the maximum and the averaged vibration amplitudes of the presented configurations. The filled lightweight concept is able to reduce the maximum amplitude by 26 dB and the average

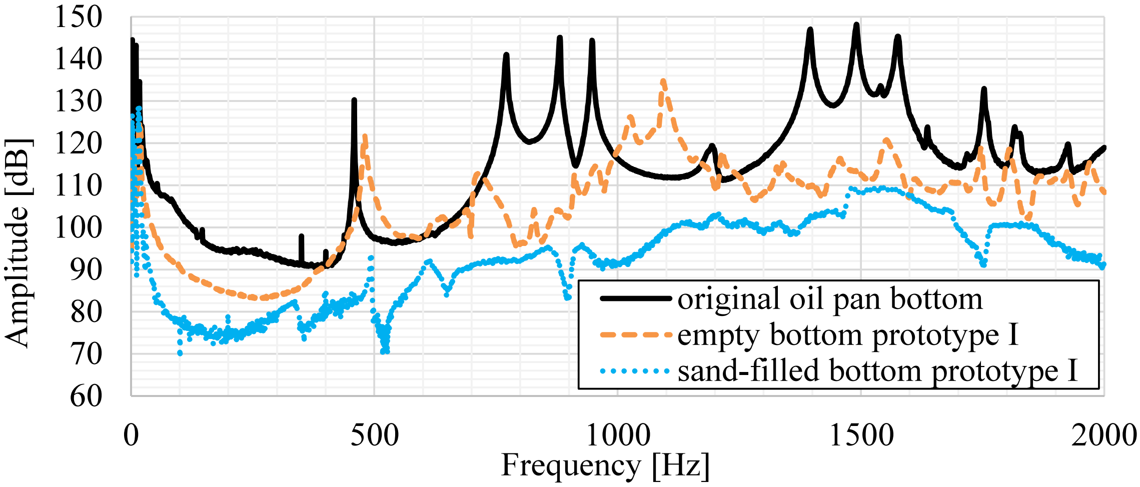

Fig. 4: Frequency response of the original oil pan bottom, the empty and filled prototype I.

amplitude by 8 dB, at a 17 % loss in weight. In a last step of the study by Duvigneau et al. [5] it was shown that the sand position influences the vibration behavior, when partial fillings are used.

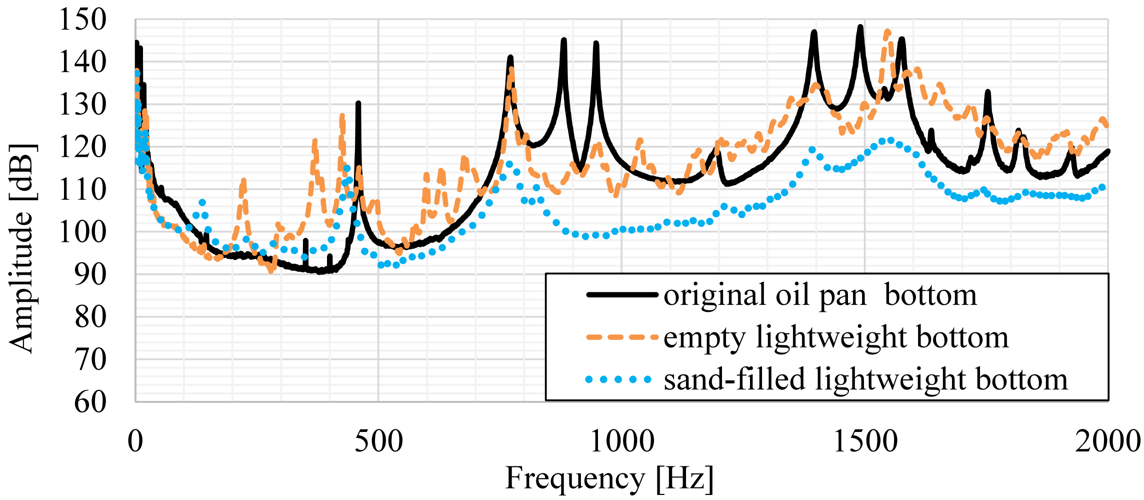

Fig. 5: Frequency response of the original oil pan bottom, the empty and the filled lightweight bottom.

Table 1: Maximum and average amplitudes of the different bottom configuration and difference to the original configuration [5].

Configuration	Maximum	Difference to max. original	Average	Difference to average orig.
Original	148.24 dB		113.38 dB	
Empty prototype I	134.84 dB	-13.40 dB	105.52 dB	-7.86 dB
Filled prototype I	109.55 dB	-38.69 dB	92.83 dB	-20.55 dB
Empty lightweight	147.24 dB	-1,00 dB	115.52 dB	+2.14 dB
Filled lightweight	121.78 dB	-26.46 dB	105.1 dB	-8.28 dB

Vibration reduction of an electric engine

Another example, where the vibration behavior is reduced using granular materials stored in several large cavities, is presented by Duvigneau et al. in [7]. In this study the acoustic behavior of an electric engine is investigated. In this context, different filling materials such as sand, balsa wood and two different foams (OC Form 500 and OC Form 1000) are compared due to their damping properties. The cavities, which are placed in the front and back side of the engine housing, are fully filled, whereby the positioning has no influence. Fig. 6 shows the sand filled part of the housing of the electric engine before it was closed by an additional metal sheets and assembled with the other parts of the housing. The corresponding frequency response of the closed part for selected fillings is presented in Fig. 7. It can be seen that both foam and sand allow a significant reduction of the vibration amplitude. Indeed, the mass of the inserted foam was significantly lower. For this reason, in section “Experimental investigation of alternative materials” additional filling materials are investigated. Furthermore, the modes are shown, which are only slightly influenced by the filling. It can also be observed that the filling causes a frequency shift.

Fig. 6: Open part of the housing of an electric engine fully filled with granular material in large cavities [7].

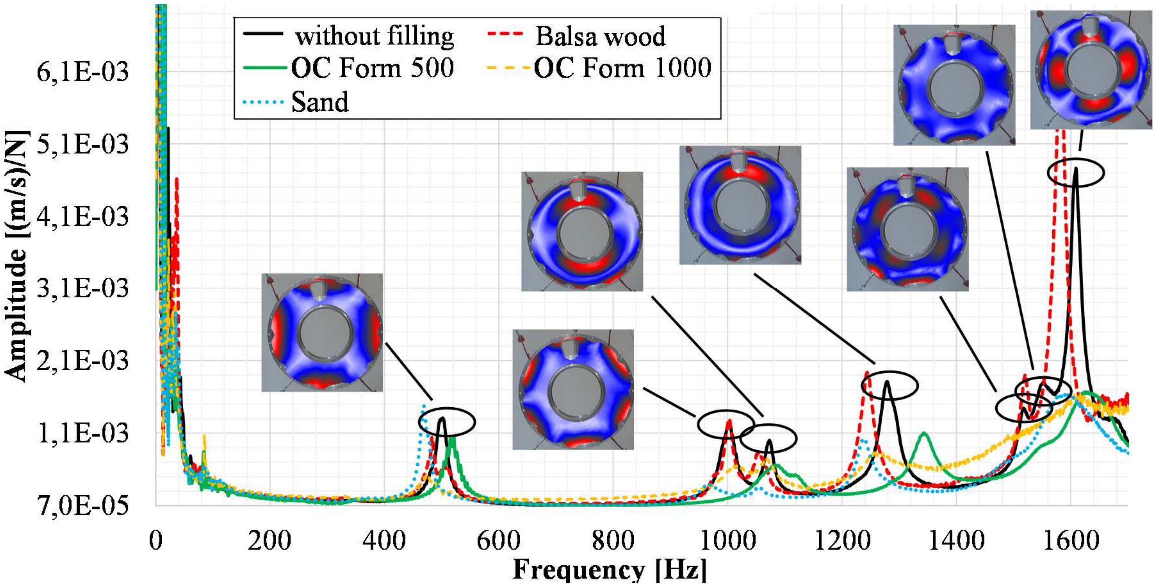

Fig. 7: Frequency responses of the housing of the electric engine without filling, with Balsa wood filling, with sand filling and two different foam fillings.

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Combination of a honeycomb structure and granular material

In [5] a significant influence of the position of the granular material on the vibration behavior of the oil pan bottom was demonstrated. In order to prevent an undesired distribution of the granular material, many small cavities are preferable, which allow an expedient filling. Therefore, a honeycomb structure is used, which offers also a high stiffness to weight ratio. The design consists of two plates. In contrast to the upper one, which seals the oil pan, the lower plate has a honeycomb structure attached and is shown in Fig. 8 with a partial sand filling in the region near the boundary of the plate. With the help of

Fig. 8: Honeycomb bottom with sand filling at the border area.

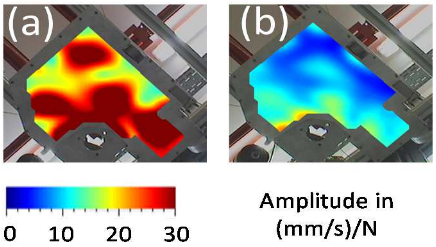

Fig. 9: Vibration behaviour of the (a) Empty honeycomb bottom; (b) Honeycomb oil pan bottom with a uniformly distributed sand filling (310 g).

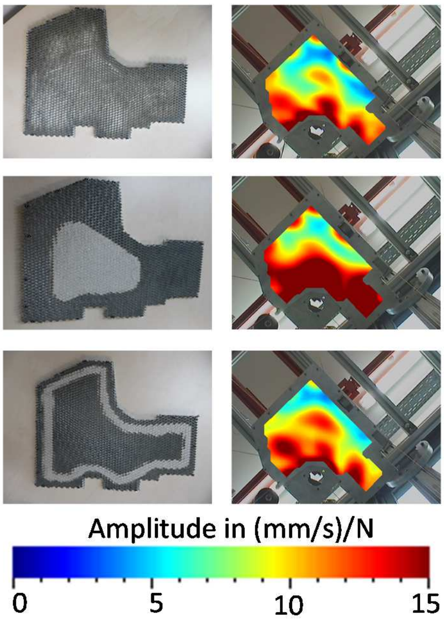

Fig. 10: Different sand distributions and the resulting vibration behaviour.

this bottom design the influence of different distributions of the granular material on the resulting vibration behavior was investigated by Koch et al. [6]. The mass of the empty bottom is 730 g while it has a capacity of 1075 g of the chosen sand. One important goal is that the novel oil pan including the granular filling is lighter than the original one. Therefore, only a partial filling with 310 g of sand is allowed. Fig. 9(a) shows the vibration behavior of the empty honeycomb bottom and (b) the vibration behavior of the honeycomb bottom uniformly distributed filled of 310 g sand. It is clearly visible, that this mass is sufficient to achieve a significant vibration reduction. Different sand distributions (310 g) and the resulting RMS values are shown in Fig. 10. It is obvious that the positioning has a significant influence on the resulting vibration behavior. It was determined that the sand has to be placed at the position of the largest vibration amplitudes, due to the fact that the dissipative effect is a result of friction and impacts between the granular particles [6]. An improved filling strategy was determined by numerical (FEM) and experimental (laser scanning vibrometer) investigations. This methodology is illustrated in Fig. 11.

Fig. 12 shows the frequency responses of the original, the empty honeycomb and the honeycomb oil pan bottom with the best experimentally determined filling. One easily observes that the filled honeycomb bottom shows an improved vibration behavior compared to the original bottom, although the honeycomb bottom has a lower mass, eve including the 310 g sand filling. Furthermore, two additional types of sands with different grain size distributions have been examined. Compared to the initially chosen sand only negligible improvements could be achieved.

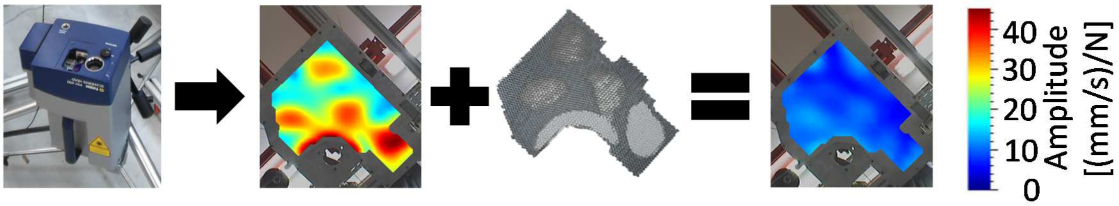

Fig. 11: Determination of the best granulate position using a laser scanning vibrometer.

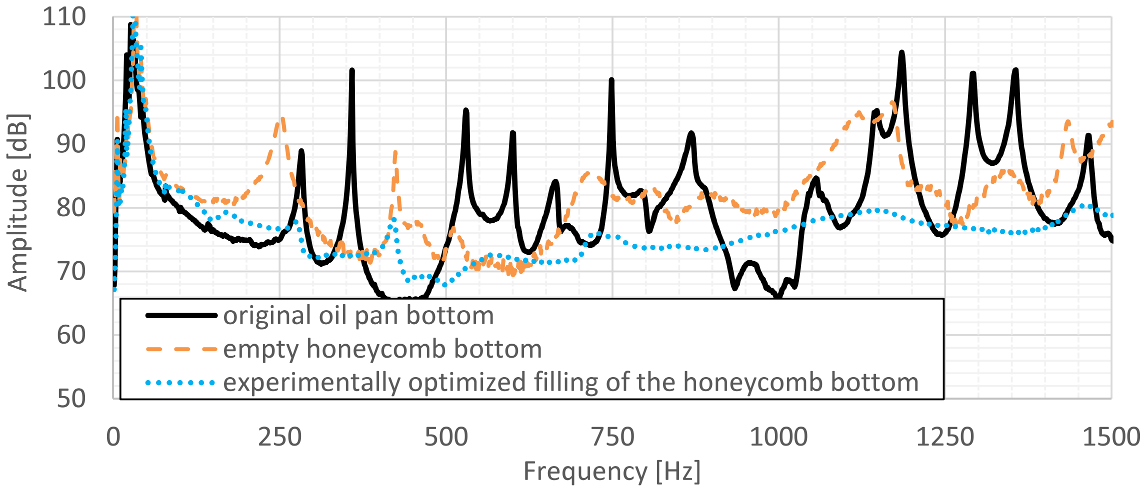

Fig. 12: Frequency response of the original oil pan bottom the empty honeycomb bottom and the honeycomb bottom with the best filling of 310 g sand.

Experimental investigation of alternative materials

In this sections the question will be answered, whether the damping effect of other materials like soft granules is better than the effect of the previously investigated sand. Besides, the influences of the shape and the grain size of the materials are studied.
Therefore, the honeycombs are filled with different types of materials. Thereby, soft granulates and soft substances like gel, different kinds of glass and corundum are tested and compared against the previously used sand. Contrary to the previous sections a simple plate is investigated, but the honeycomb dimensions are the same as in the previous. Rectangular plates (300mm x 600mm) were used in this study. In contrast to the previous experiments, the plate is excited by a shaker with a coupling rod instead of an impulse hammer, in order to stimulate a higher frequency range using white noise. Fig. 13 shows the experimental setup of this investigation.

Filling materials

We investigated 8 different materials such as (a) sand, (b) granular rubber, (c) two different grain sizes of granular glass, (d) corundum, (e) polystyrene, (f) glass balls, (g) silicone and (h) gelatin based gel. Fig. 14 depicts the investigated materials (a)-(f). Material (a) is the sand exhibiting the best performance in previous studies [6]. This sand can now be used as a reference to assess the properties of the other filling materials. Moreover, silicone (g) and a gelatin based gel (h) are used as soft nongranular material. As an example for a soft granular material granular rubber (b) is used. The influence of the particle shape can be roughly estimated by comparing the granular glass with the glass balls. The glass balls have a diameter of 3 mm and a low inner friction coefficient. Consequently, a low friction loss is expected. Two different grain sizes (0.2-0.4 mm and 0.4 – 0.6 mm) of granular glass (c), are investigated, in order to determine this influence. To determine the

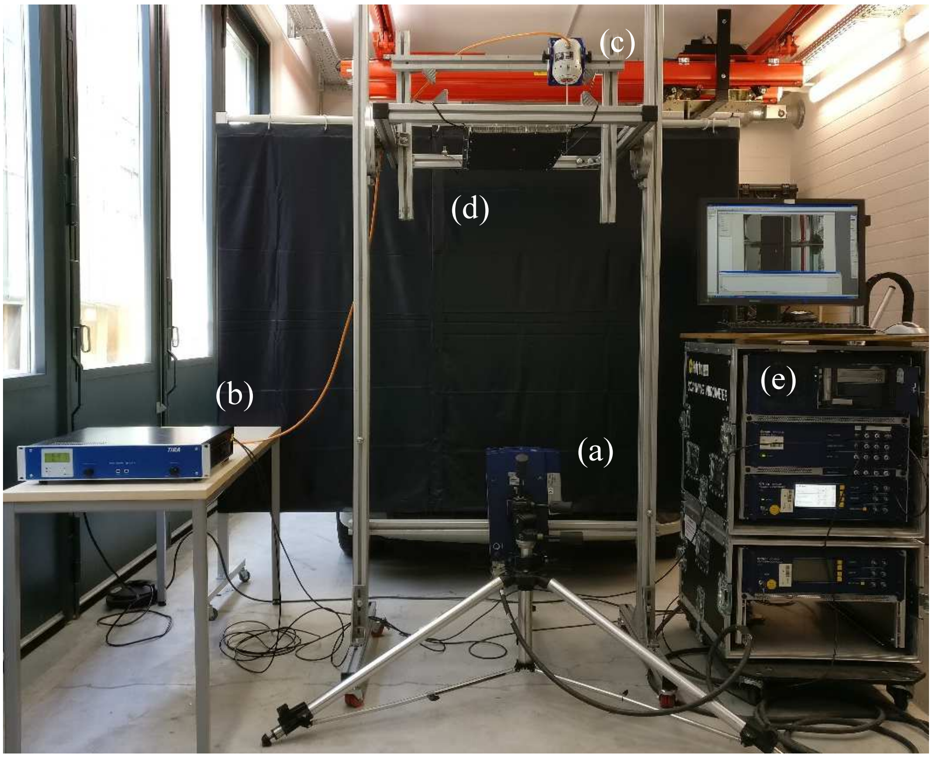

Fig. 13: Experimental setup: (a) Laser-Scanning-Vibrometer; (b) Amplifier; (c) Shaker; (d) Honeycomb plate; (e) Control and postprocessing unit.

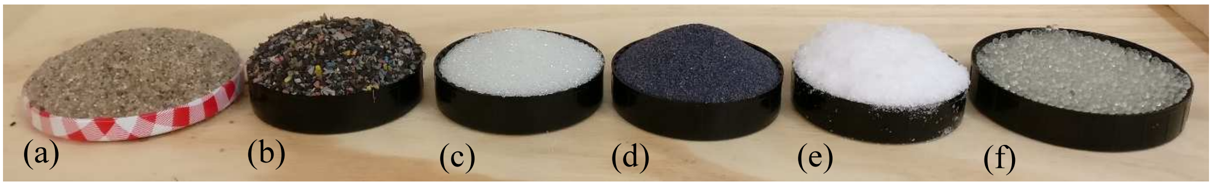

Fig. 14: Different investigated granular materials: (a) Sand; (b) Granular rubber; (c) Granular glass; (d) Corundum; (e) Polystyrene; (f) Glass balls.

influence of the inner friction, corundum (d) with a high friction coefficient is examined. Fig. 14(e) shows polystyrene, which is a very light granular material.

Results

In Fig. 15 the frequency response for a sand and corundum filling is compared. As long as no other specification are given, 620 g of the specific filling material are used, which is equal to the mass of the honeycomb plate. In addition, the frequency response of the empty honeycomb plate is shown in gray. Up to 165 Hz a negligible reduction of the vibration amplitudes is observed while a significant frequency shift towards lower frequencies is seen. The amplitudes of the mode at 166 Hz are even slightly elevated. Above 166 Hz a significant vibration reduction is realized. The aforementioned frequency shift can be attributed to the mass effect of the filling. The vibration behavior of sand and corundum is similar over the entire frequency range. The frequency response of glass particles of different grain sizes and shapes are shown in Fig. 16. It is easy to recognize that the frequency responses are quite similar. Apparently it is not of importance whether spheres or granular particles are used, also the grain size seems to have hardly any influence. The comparison of sand and glass balls is depicted in Fig. 17. Again, there is hardly any difference between the different granulates. The frequency response of the honeycomb plate filled with granular rubber, which is used as an example of soft granules is shown in Fig. 18 and compared to sand. Up to 50 Hz the vibration behavior is quite similar. At higher frequencies, a significant vibration reduction is seen using the granular rubber. Obviously, the soft granules cause higher dissipative effects than the stiffer ones. This leads to the question how materials such as silicone affects the vibration behavior, since it is soft but not granular. Fig. 19 compares silicone and granular rubber. While 620 g of granular rubber completely fill the honeycomb structure, 620 g of silicone are filling only a few cells. The lower frequency level of the plate with granular filling is clearly visible. A complete filling of a gelatin-based gel compared to granular rubber is shown in Fig. 20. The mass of this gel is 1300 g, thus twice as much as the rubber. Obviously, a larger frequency shift occurs caused by the additional mass. The vibration amplitudes are in the whole frequency domain higher than for the granular filled plate. As a further filling, polystyrene is tested and compared with granular rubber. Due to the low

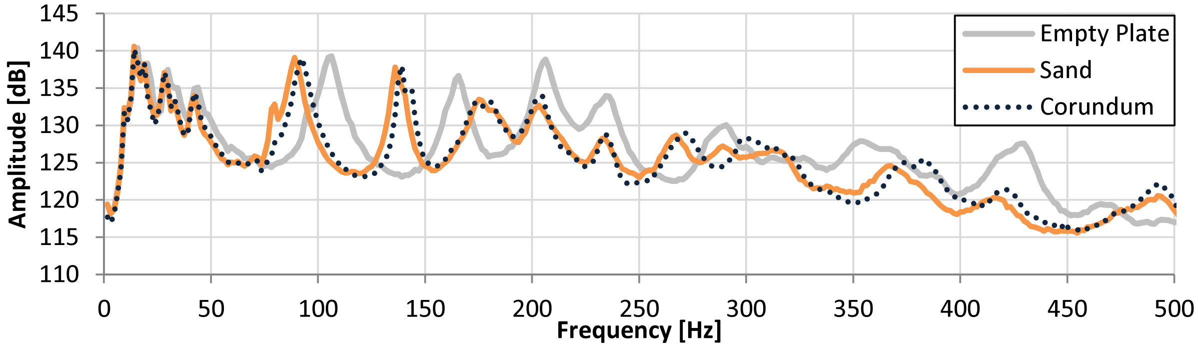

Fig. 15: Frequency response of the honeycomb plate without filling, a filling of sand and corundum.

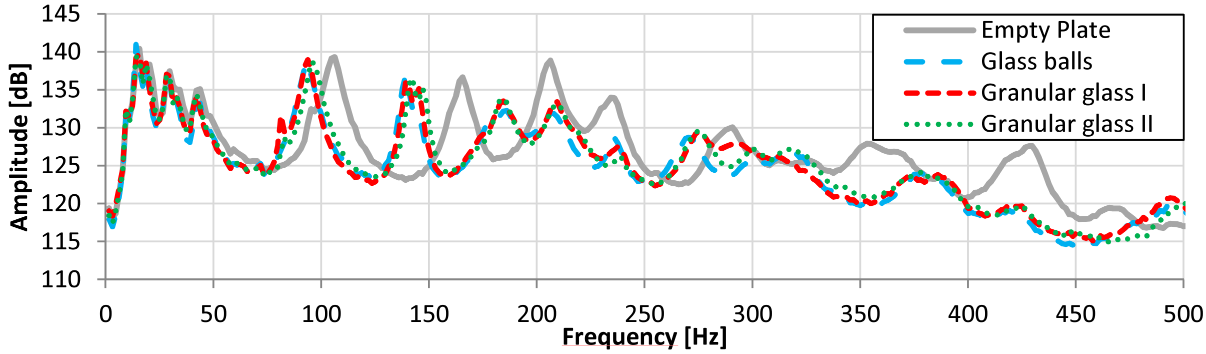

Fig. 16: Frequency response of the honeycomb plate without filling, a filling of glass balls and granular glass in two grain sizes.

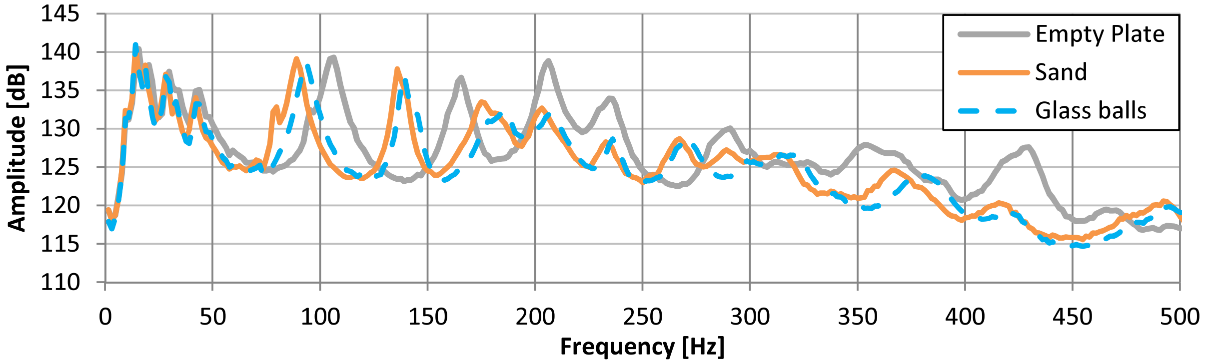

Fig. 17: Frequency response of the honeycomb plate without filling, a filling of sand and glass balls.

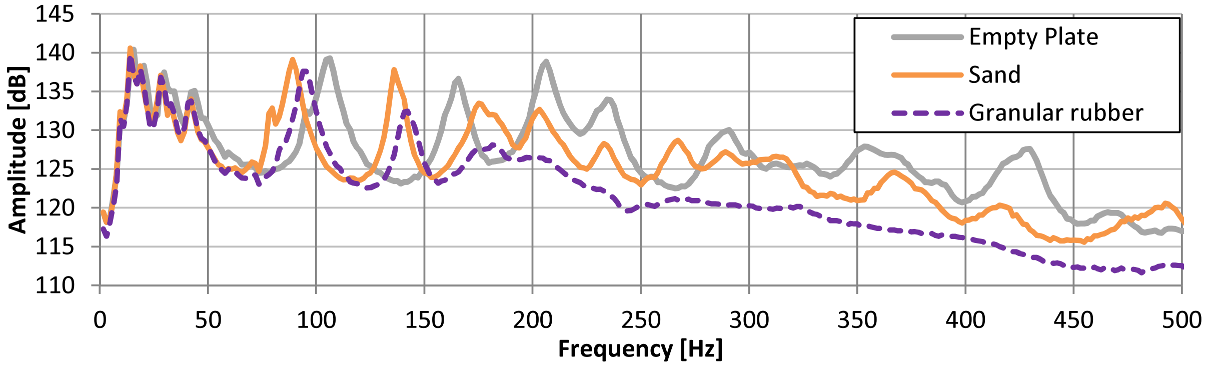

Fig. 18: Frequency response of the honeycomb plate without filling, a filling of sand and granular rubber.

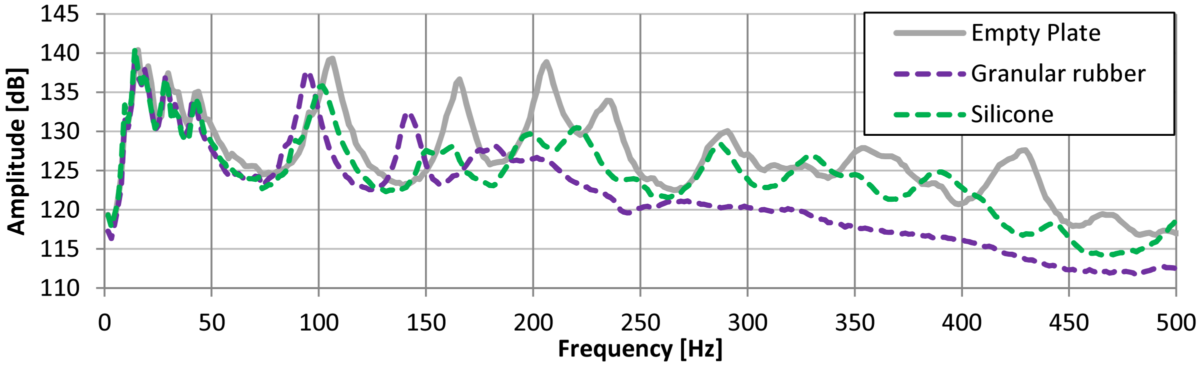

Fig. 19: Frequency response of the honeycomb plate without filling, a filling of granular rubber and silicone.

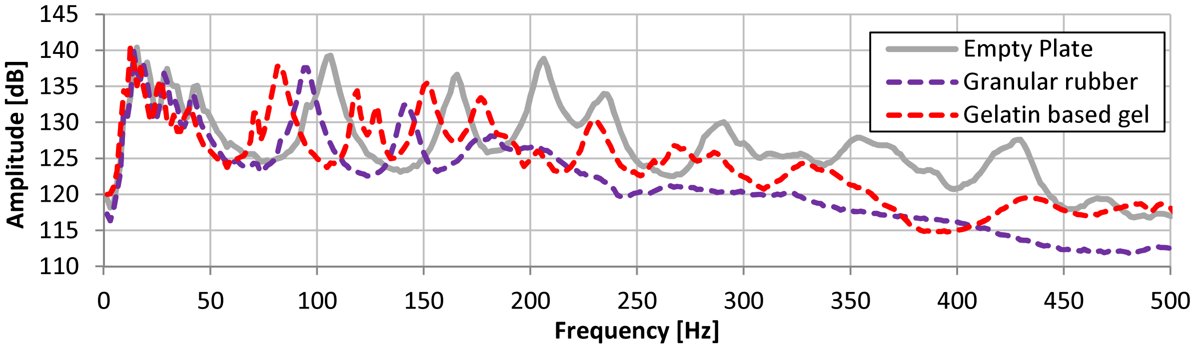

Fig. 20: Frequency response of the honeycomb plate without filling, a filling of 620 g granular rubber and 1300 g of a gelatine base gel.

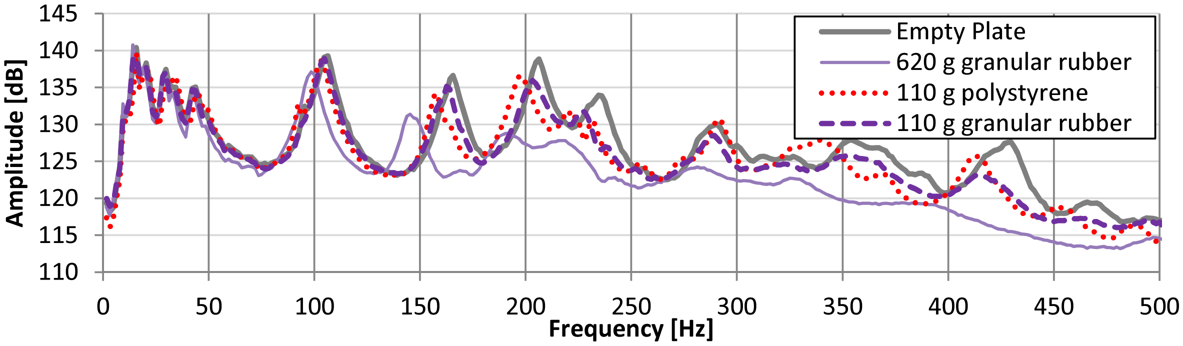

Fig. 21: Frequency response of the honeycomb plate without filling, a filling of 110 g polystyrene and 110 g granular rubber.

density of polystyrene, only 110 g can be filled into the honeycomb structure. Fig. 21 compares the vibration behavior of polystyrene and granular rubber for a filling of 110 g. Even the small mass of 110 g reduces the peak amplitudes in the range of 125-250 Hz each by 2 dB. Which of the two materials has the better damping effect depends on the frequency under consideration, but the vibration behavior is largely comparable. In summary, it can be stated that the granular rubber and polystyrene have the best damping effect of all investigated materials. However, only a small amount of polystyrene (110 g) can be filled in the structure due to the limited volume of the honeycomb plate. A full filling with granular rubber (620 g) would cause significant lower vibration amplitudes (see Fig. 21).

Attenuation of selected modes

In this section it is examined, whether it is possible to suppress selected modes by an adapted positioning of the granular material in the honeycomb structure. Therefore, the same plate and experimental setup as depicted in Fig. 13 are used. Fig. 22 shows the frequency response of the empty honeycomb plate and selected eigenmodes (a)-(d). In order to show whether it is possible to suppress certain modes, the best investigated material, granular rubber, is used. In addition, the frequency response of a partial filling of 234 g (e) is presented. The filling material is distributed at the positions with large amplitudes

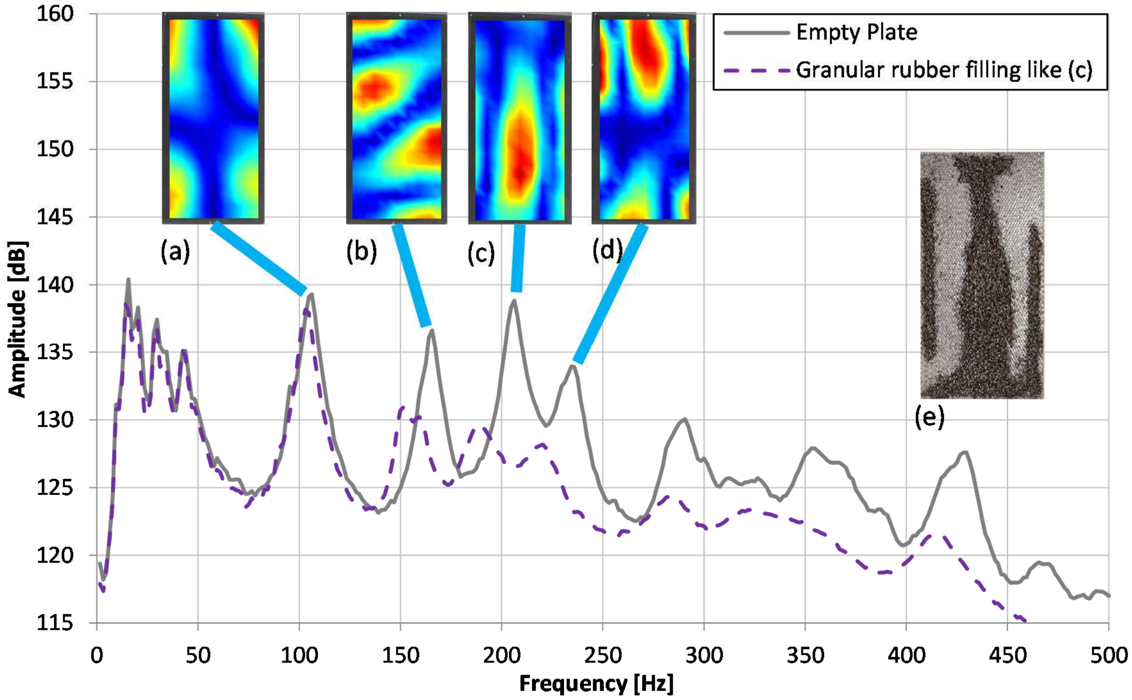

Fig. 22: Frequency response of the empty honeycomb structure and with a filling of 234 g granular rubber (e). (a) – (d) show some eigenmodes, whereby (c) is the mode, which should be damped with the filling.

in the empty plate at 206 Hz (c). It is clearly visible that this mode is strongly damped. The mode at 106 Hz (a), which has low amplitudes at the positions of the filling, is nearly unchanged. The filling has a large influence on the modes at 166 Hz (b) and 233 Hz (d), but not as strong as the mode at 206 Hz (c). Consequently, it is possible to increase the damping for selected modes in a certain frequency. However, the filling also has an influence on other modes. The strength of the influence depends on whether the greatest amplitudes take place in the same regions.

Comparison of the honeycomb plate under horizontal and vertical suspension

Finally, in this section the question is answered, how does the vibration reduction behavior in a horizontal and vertical suspension differ. Therefore, the plate and experimental setup depicted in Fig. 13 is rotated by 90°. Fig. 23 shows the frequency response of the empty and glass ball filled honeycomb structure horizontally and vertically mounted. One clearly sees that the amplitudes of the horizontal and vertical empty plate are quite similar although a frequency shift is visible. This results from the changed boundary conditions. While the amplitudes of the empty configurations are largely the same, they are significantly influenced in certain frequency ranges in the filled vertically mounted variant. This was unexpected, as the granular material is now not perfectly in contact with the measured surface. Instead the main direction of motion is orthogonal to the gravitational force. Consequently, the particles can move more easily compared to the case of the horizontally mounted plate and therefore they can dissipate more energy by impacts and friction between each other.

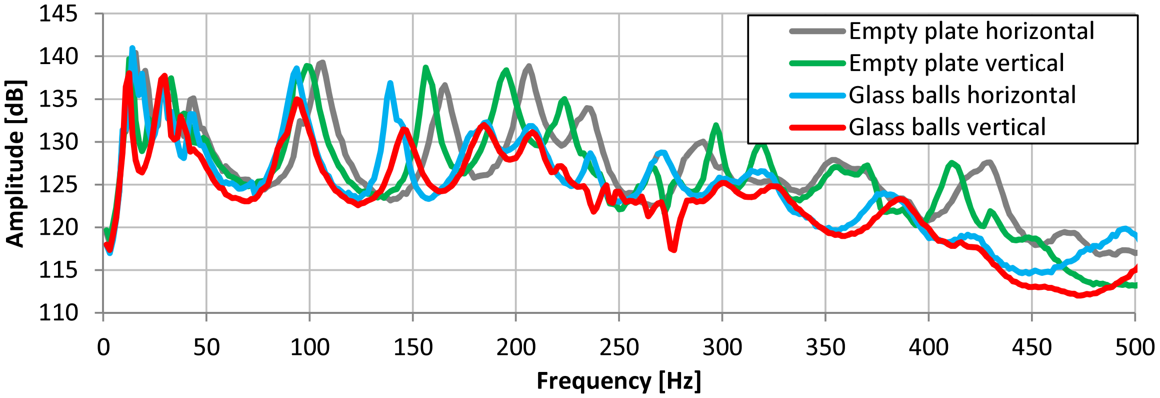

Fig. 23: Frequency response of the honeycomb plate without filling and filled with glass balls.

Summary

The previous studies have shown that it is possible to reduce the vibration behavior without additional mass, using granular materials. Therefore, two concepts were presented, which use one or many cavities for the filling with granular materials. This investigation has shown that soft particles such as granular rubber have a larger damping effect than stiffer ones. It has also been shown that neither size nor shape have a significant influence on the vibration behavior, using solid granules. Additionally, the granular rubber results in an increased vibration reduction than a gel, which is soft but not granular.

It could be confirmed that it is possible to reduce the amplitudes of chosen modes stronger than the remaining ones. However, the filling also has an influence on the other modes, depending on the similarity of the modes.

In a last step it was shown that the presented lightweight concept can be used almost independent of the mounting (vertically or horizontally). Hence, the damping effect is only slightly effected by orientation.

Acknowledgements

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