Experimental Investigations of Flexible Wall Effects in Helmholtz Resonators for Aircraft Engine Acoustic Liners

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Acoustic liners working like Helmholtz resonators offer an effective way to dampen tonal noise in aircraft engines. In order to broaden the bandwidth of a Helmholtz resonator, we added flexible walls that result in an additional low frequency dissipation. We investigated different parameters of the concept with a modular setup. In this paper, the results of measurements for a resonator with a flexible wall – representing the basic element of an advanced liner concept - and its potential to dampen lower frequencies are shown. The measurements are conducted at an aero-acoustic wind tunnel for multiple combinations of up to two resonators and up to four flexible walls with different parameters such as material, thickness, distance, position, orientation and shape. In this paper we show which parameter has an influence on the dissipation caused by the flexible wall. An additional dissipation occurs at specific material parameter whereas the geometric parameters alter the frequency of the additional dissipation.

I.Nomenclature

c	=	speed of sound
f_0	=	resonance frequency, frequency of highest dissipation
L	=	neck length of a Helmholtz resonator, here: thickness of the face sheet
S_0	=	open area of Helmholtz resonator
V_0	=	resonator volume of Helmholtz resonator

II.Introduction

Aircraft noise is a major source of aviation-based emissions of concern especially near airports. One source is the fan noise emitted at a specific frequency e.g. from the fan-stator-interaction. Helmholtz resonators offer a good possibility to dampen a specific frequency. Therefore, this type of resonator is used in acoustic liners at the inlet of aircraft engine nacelles for damping especially the fan noise. These acoustic liners typically consist of a honeycomb structure covered by a perforated face sheet. If the whole area has the same face sheet and structure, the acoustic liner is tuned to a single frequency (Single degree of freedom, SDOF liner). Furthermore, there are liner concepts which use two (Double degree of freedom, DDOF) [1] or more (Multi degree of freedom, MDOF) degrees of freedom to

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broaden the damped frequency range by the acoustic liner's design. This is useful as the fan emitted frequencies alter by the rotating speed which is, in turn, dependent on the needed thrust of the engine. One possible design of MDOF liners is a liner with two layers of cells with a so-called "mesh-cap" in between [2–4]. Another concept deals with electric driven changes of the liner cell volume [5–7]. Unfortunately, the Helmholtz resonators need a big volume in order to dampen low frequencies expected for new large, slowly rotating aircraft engine fans.

In order to reduce the emissions at their source, larger fans will be used in future aircraft engines for higher by-pass-ratios. These fans rotate slower than the fan in current engines with lower by-pass-ratios and will therefore emit lower frequencies coming from the vanes passing blades. As a consequence, to dampen lower frequencies with a SDOF liner, larger volumes and/or greater depths for the acoustic liners are required. Due to the larger fans, the whole engine will be bigger too, which leads to a higher drag. In order to integrate the acoustic liners into the fan intake, the liner structures have to maintain current depth limits or even become smaller so that the drag of the whole engine will not be further increased. This implies that new liner concepts are necessary. Various new concepts already exist such as concepts with folded cavities [8], actively changing cavities or passive concepts that tackle lower frequencies. One of these passive concepts is a drum-like silencer dampening the noise by vibrations of a flexible wall [9,10]. These flexible walls face a high risk of demolition when placed directly in the fan's intake due to chemicals (e.g. anti-ice fluids, engine oil, kerosene), debris (e.g. ice, sand, hail, birds) or just mechanical loads and the air stream itself. Therefore, this concept needs protection which also might have an influence on the acoustic performance and adds weight.

In a previous investigation the researchers Knobloch, Dannemann et al. [11,12] found additional acoustic dissipation by replacing rigid walls with flexible walls between adjacent resonators. The underlying physical mechanism and specifically the influencing parameters for the application of the flexible walls were not explored, so further investigations are necessary.

Such further investigations represent the core of the research presented here. Most of the basic geometrical and material parameters are addressed in this paper. Therefore, a generic setup consisting of modular elements representing the basic elements of this liner concept is used for a comprehensive experimental investigation. This investigation includes a single resonator to understand the basic effects and measurements with two resonator which can be coupled via the flexible walls but also are measured in an uncoupled setup.

The paper is structured as follows: First, in section III the different experimental settings are explained and in the next part the corresponding results and their discussion are shown. This will be followed by a conclusion and an outlook.

III. Materials and Methods

In order to understand the mechanisms and the relevant parameters of the flexible walls, we undertake different experiments. These experiments are carried out at the DUCT-R (Duct Acoustic Test Rig, rectangular cross section, further called DUCT) test facility of the German Aerospace Center (DLR) in Berlin.

The measurements are conducted with a "standard" Helmholtz resonator (Fig. 1 a)) and the same resonator with an additional flexible wall (Fig. 1 b)). A schematic view of the concept is shown in Fig. 1.

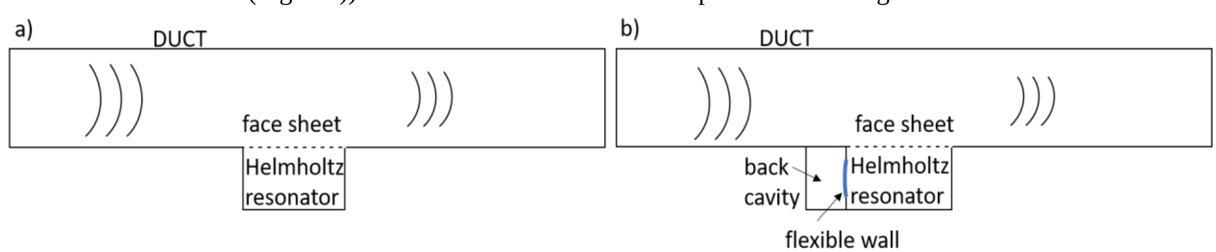


Fig. 1 Schematic view on the concept of Helmholtz resonator without (a) and with (b) flexible wall

The DUCT has a cross section of 60 mm x 80 mm. The measurements with only one resonator are in general conducted at the shorter side and the measurements with two resonators as well as selected measurements with one resonator are conducted at the 80 mm side. The resonators section is placed between two microphone sections with five microphones each, as shown in Fig. 2. The microphones are flush mounted with the inner DUCT wall. The microphones do not have the same spacing to each other to avoid singularities in the wave decomposition. At both ends of the DUCT there is an anechoic termination in order to reduce end reflections (not shown in Fig. 2). The calculation of the scattering coefficients, namely the transmission, reflection and dissipation of acoustic energy is detailed in [13].

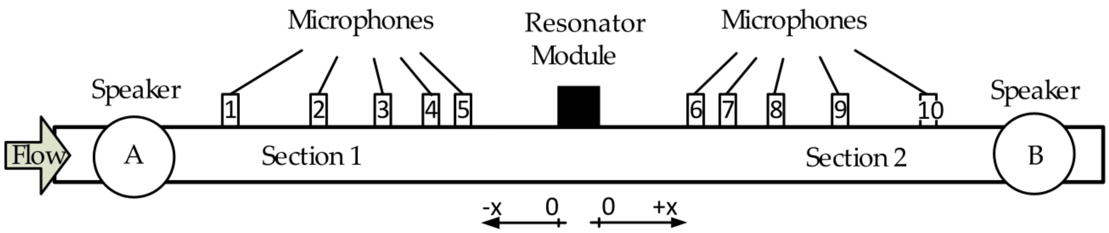


Fig. 2 Schematic view of the DUCT test facility

The sound in the main duct is excited for each measurement with a single sine tone with speaker A and speaker B, one after the other. The measured frequencies range from 204 Hz to 2040 Hz which is under the cut-on limit for higher order modes in the DUCT. We used smaller steps at lower frequencies as the focus on this investigation is on damping beneath 1000 Hz whereas bigger frequency steps are used in higher frequencies. For all measurements the emitted sound pressure level is at 110 dB without flow. This is due to the fact that we want to focus on the physics inside the cell without interference of face sheet non-linearities, as the Helmholtz resonator's effects with flow may cover small changes anticipated for the acoustic dissipation by variations of the cell setup or the flexible wall.

The modular test rig consists of a cuboidel resonator (35 mm x 35 mm x 50 mm) where five sides can be used for extensions, connections or elements which carry flexible walls, and the sixth side is attached to the DUCT via a face sheet. In Fig. 3 the resonator (1) is shown mounted to the DUCT (5) and with a flexible wall (2), a big back cavity (3) and a closing plate (4). The resonator has a wall thickness of 10 mm which is blanked off when no flexible wall is attached. This blank is shown in Fig. 3 as number 1. The flexible wall is clamped between two 3 mm aluminum frames (see Fig. 4). By using a flexible wall, the resonator's volume is increased by 20 % (35 mm x 35 mm x 10 mm) compared to the standard resonator.

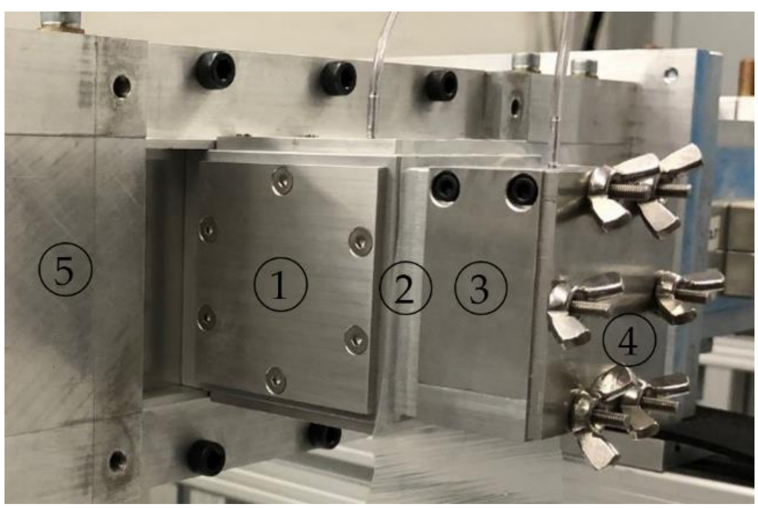


Fig. 3 Resonator assembly with 1) resonator; 2) plate holder with flexible wall; 3) back cavity; 4) closing plate attached to the DUCT (5). The assembly is covered by a face sheet which constitutes the interface to the main duct (not visible here)

The flexible walls are put between two aluminum plates which are tightened by ten screws, as shown in Fig. 4, to ensure a clamped boundary condition. Both aluminum plates have the same cut out and additionally six further holes to assemble them to the resonator by six threaded rods. The flexible material can vibrate in the area of the cut outs, so this part is considered as the active area. The cut outs shapes are circular, square (both 15 mm diameter or side length respectively) and rectangular with a size of 15 mm x 26 mm (see Fig. 4), which can be used horizontally or vertically.

For further investigation of the active area, two additional circular plate holders with cut out diameters of 23 mm and 30 mm are manufactured.

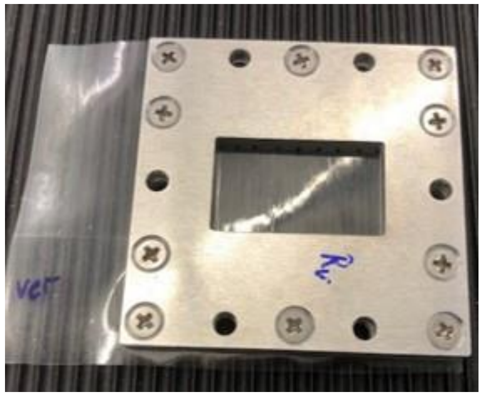


Fig. 4 Plate holder with rectangular cut out and flexible wall

The flexible walls are either made of aluminum sheet metals or plastic films with different thicknesses and materials (mainly different regarding the Young's Modulus). The Young's modulus is a material parameter for the elasticity. A lower value in MPa indicates more elasticity and therefore flexibility of the material. A list of materials, their thicknesses and average Young's modulus' can be seen in Table 1. The X indicates that the combination has been measured in this investigation in the one resonator setup.

Table 1 Measured materials for flexible walls with their Young's modulus and thicknesses

Thickness mm	Aluminum (Alu) 70000 MPa	Polypropylene (PP) 1600 MPa	Thermoplastic Polyurethane (TPU) 16 MPa	Polyamide 6 (PA6) 800 MPa	Polyphenylene Sulphide (PPS) 2400 MPa	Polyether Ether Ketone (PEEK) 2800 MPa
0.01	X					
0.05	X					
0.1	X	X	X		X	X
0.2		X				
0.3			X			
0.4				X		

We placed a back cavity and a closing plate (both aluminum) on the other side of the flexible wall and tightened everything by nuts. The whole assembly can be seen in Fig. 3. For all measurements the same face sheet geometry is used. The face sheet has 18 evenly spaced holes with 1.5 mm diameter and a thickness of 2 mm, yielding a porosity of 2.6% (based on the 35x35 mm² area).
Two different back cavity lengths are designed for the single resonator measurements with depth (length) of 15 mm and 25 mm, respectively. Both back cavities have a quadratic shape of 35 mm x 35 mm.
The modularity of the test object enabled measurements with different volume ratios between the resonator and the back cavities are possible.

Initially, a principal component analysis is used to minimize the needed measurements to find out the main effects. The measurements show a very high repeatability when the flexible wall is assembled with a maximum torque of 0.2 Nm. Different measurements that are repeated after two months, show a very high congruency with each other, even if two different persons assembled them. Many more repetitions of assembly and measurements support this finding.

After the measurements with one resonator, measurements with two resonators are conducted in order to investigate effects that may occur with coupled resonators.
The measurements with two resonators are taken with coupled and uncoupled resonators. In order to couple the two resonators with each other outside the DUCT, some modifications had to be made. First of all, it is necessary to join them by an external fixator put at both long sides (see Fig. 5 a)) in order to ensure a acoustically tight connection. Second, another small cavity with a depth of 6.3 mm is needed to replace the middle flexible wall when not used.

Varying the axial distance (in five steps) between main resonator cavities, face sheet perforation for each resonator is kept constant. The face sheet geometry for all measurements remains the same.

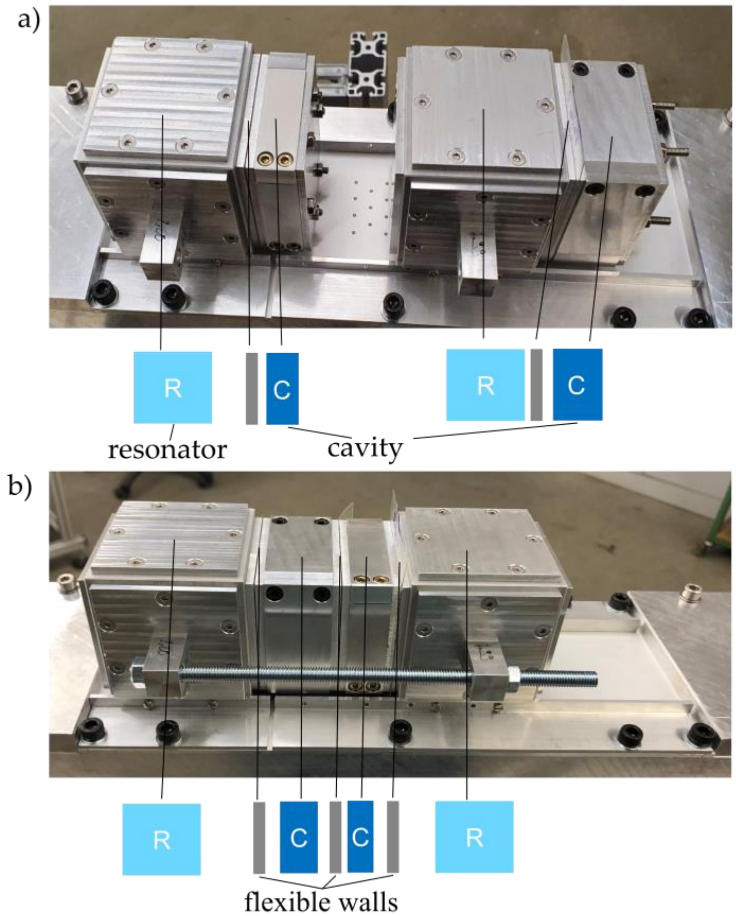


Fig. 5 Picture and schematic view of a) an uncoupled pair of resonators with one flexible wall for each resonator and b) a coupled pair of resonators with external fixator and three flexible walls between the resonators. Same distance used between resonators in a) and b)

With the described setups we investigated the following aspects in order to understand the impact on acoustic dissipation.

At the single resonator the following aspects are varied:

A1) The position of the back cavity compared to the DUCT

A2) The material of the flexible wall (and for selected cases the material thickness)

A3) The shape of the cut out where the flexible wall can vibrate

A4) The size of the back cavity

A5) The number of flexible walls

At the two-resonator assembly the flexible wall’s shape, material, thickness and position remained the same but the following aspects are varied:

B1) The spacing between adjacent resonators and therefore, in selected cases, the back cavity size

B2) The interaction between two resonators with flexible walls

IV. Results and Discussion

The separation of the different effects is essential to correctly understand the results. First, the single resonator setup will be discussed. Second, the two resonators setup as well as effects occurring due to the coupling of two resonators will be discussed. All findings will finally be used to predict and understand the effects of a liner sample with flexible walls. All results use the dissipation of acoustic energy taken by the resonator and the flexible wall as the relevant quantity. A certain part of the total acoustic dissipation is expected to be directly linked to the movement of the flexible wall. A certain influence on the main dissipation peak – stemming from main resonator/face sheet combination – can be expected as well.

A. Measurements with one resonator

- **A1: Position of the flexible wall/back cavity with respect to the main duct**

The position of the flexible wall (parallel or orthogonal compared to the DUCT), has only a minor influence on the dissipation, as shown in Fig. 6. The dissipation at 600 Hz occurs from the Helmholtz resonator. The additional dissipation at lower frequencies is caused by the flexible wall, as can be seen in Fig. 7. There is a small difference between both measurements in the additional dissipations. The shape of the blue curve differs from the red one because of a small frequency shift. This results, because of the distinct measured frequencies, in a lack of resonance peak as the resonance frequency is in the middle of both measured frequencies. However, the difference is small and almost neglectable. Therefore, later measurements are conducted with the flexible wall parallel to the DUCT due to easier assembly. Especially on the main dissipation peak there is no influence of the flexible walls position. The main peak at 612 Hz is caused by the Helmholtz resonance and is dependent on the volume and not on the resonator depth.

The results also show that for further assemblies e.g. in liners the whole depth can be used for the resonator itself because the flexible wall and back cavity can be put parallel to the resonator cells. This finding holds true for low frequencies with wavelengths larger than the resonator dimension and would need additional attention for acoustic wavelengths in the range of or below resonator dimensions. The dissipation's dependency on the resonator volume is also proven by other measurements which will be presented later in this paper.

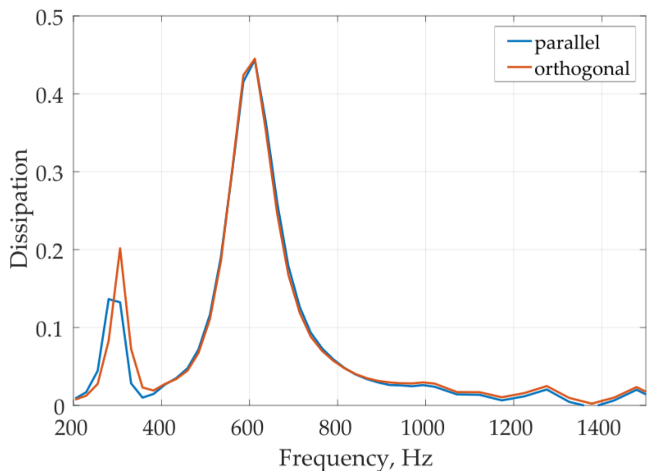


Fig. 6 Comparison of measurements with flexible walls parallel or orthogonal compared to the DUCT

- **A2: Material of flexible wall**

The main result from the one resonator measurements is the additional dissipation caused by the flexible wall's material. In Fig. 7 the dissipation over the important frequency area of 200 Hz to 1000 Hz is shown for different materials and thicknesses and the resonator without a flexible wall (here called Reference). The flexible walls have a circular cut out and the same back cavity size for all measurements shown in Fig. 7. In the left plot all materials without a major effect on the dissipation are shown whereas in the right plot the used flexible walls' materials with an effect are plotted. As can be seen in Fig. 7 b), the flexible walls made of TPU show an additional peak at lower frequencies. All other materials only show the regular Helmholtz resonance as the flexible walls seem acoustically stiff. This results in no difference between the reference and the measurements with flexible walls (Fig. 7 a)). The comparison in the right picture of Fig. 7 also shows that the additional dissipation peak at lower frequencies seems to be dependent on the flexible wall's material and thickness. The thickness is presented by the numbers in the legend in 10^{-1} mm in Fig. 7. As can be seen, only flexible walls out of aluminum or TPU show any effect on the dissipation. An additional dissipation peak only occurs for measurements with a flexible wall made of TPU. This additional dissipation therefore seems to be material-dependent. Comparing the measurements with TPU walls, one can see that there is also a difference between the two curves (TPU_01 and TPU_03) even though they have the same setup but only different flexible wall thicknesses. Aluminum has a more than 4000 times higher Young's modulus value than TPU, but both show an effect on the dissipation. This highlights that instead of the Young's modulus the flexural rigidity is the important factor of the flexible wall's dissipation. The flexural rigidity is at the same order of magnitude for both TPU materials and the 0.01 mm aluminum, whereas the aluminum plates of 0.03 mm and 0.05 mm show a two orders of magnitudes higher flexural rigidity. This dependency on the flexural rigidity can also be confirmed by looking at the different dissipation curves of aluminum in Fig. 7 b). The thinner the aluminum sheets the dissipation frequency decreases and on the other hand with thicker aluminum sheets the dissipation curve almost show the same results as for the reference measurement. Looking at the TPU flexible walls in Fig. 7 b), blue and yellow lines, one can see that they result in slightly higher frequencies than the reference for both thicknesses. However, it has to be stated, that the dissipation curves of the TPU material with 0.1 mm thickness are not consistent over different measurements. The material is too flexible to be mounted in in a repeatable manner. For measurements that will be used for validation, the flexible wall out of thin TPU is not applicable. In [14] the validation of a semi-analytical model with the measurements with flexible walls out of 0.3 mm TPU is shown. The results show also a good agreement between measurements and calculations.

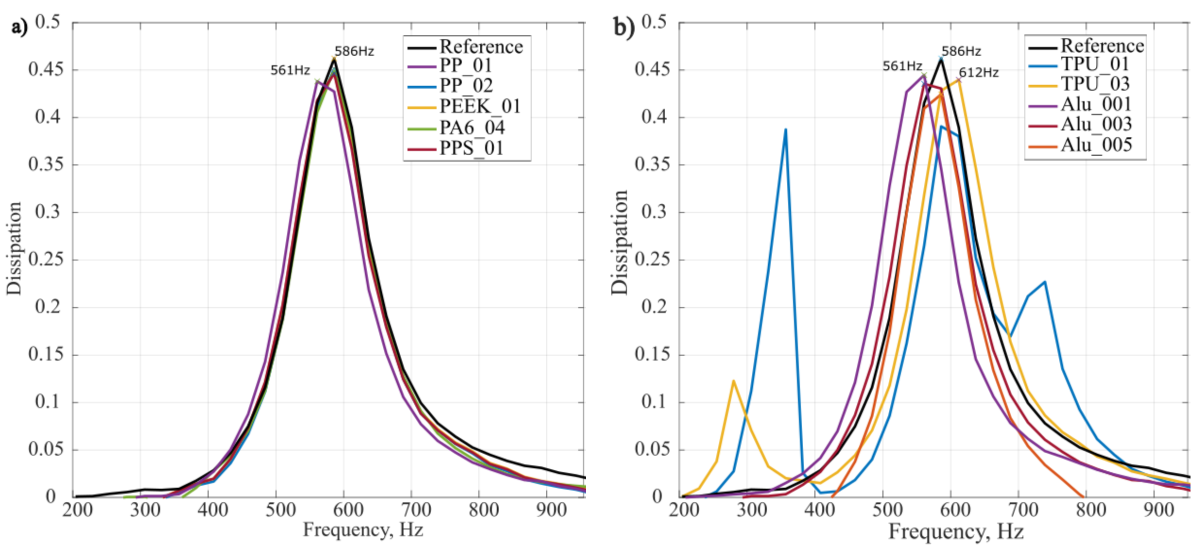
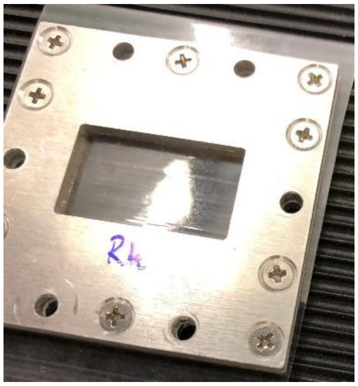


Fig. 7 Dissipation of resonator with flexible wall of different materials and thicknesses (in 10^{-1} mm) compared to the reference resonator (without flexible wall) a) with materials with high Youngs' modulus and b) with low Youngs' modulus (TPU) or high Youngs' modulus and very thin walls (Alu)

- **A3: Shape and orientation of flexible wall**

Another important parameter is the shape of the flexible wall's active area. Therefore, measurements with circular, rectangular and square cut outs are conducted.

There are differences in the additional low frequency dissipation, mostly at rectangular cut outs when comparing the results of repeated measurements. A series of 50 measurement with new mounting of the flexible wall for each individual measurement revealed the sensitivity to the mounting conditions. A torque limit of 0.2 Nm for the relevant connections must not be exceeded in order to avoid pre-tensioning or even static deflection (Fig. 8) of the flexible material. Another factor is the orientation of the flexible wall itself with respect to the cut out's orientation. This might be caused by varying thicknesses or mechanical properties within the flexible wall due to the manufacturing process (horizontal lines inside the plastic film visible in indicate quite clearly the manufacturing direction). As the walls flexural rigidity is found to be an important factor for the dissipation, a small difference in materials thickness would cause a difference in the dissipation curves. This may result in different vibration frequencies or even vibration mode orders.



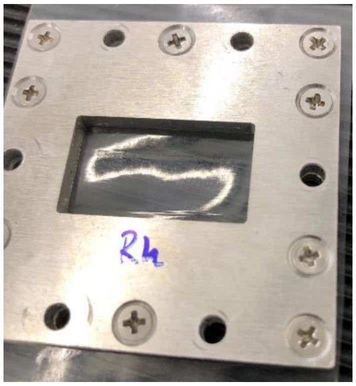


Fig. 8 Flexible walls without tension a) and with tension due to too high torque b)

The dissipation for three different shapes is presented in Fig. 9. As can be seen, the rectangular shape in both orientations shows two additional dissipation peaks whereas the other two shapes only show one. This underlines that the former called material-dependent dissipation is also dependent on the shape or active area of the flexible wall.

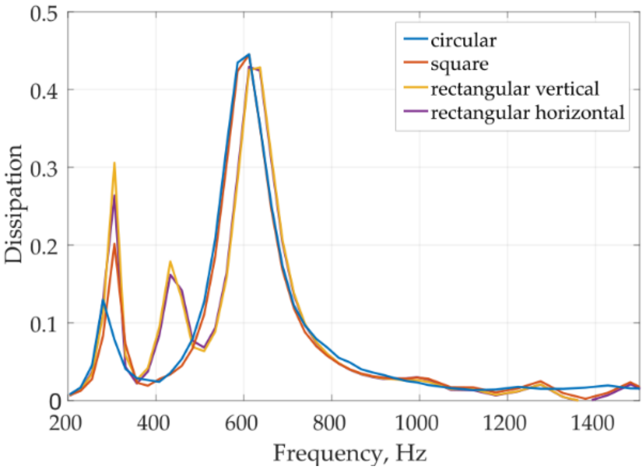


Fig. 9 Dissipation of TPU with 0.3 mm thickness at different cut out shapes

In order to find out whether the shape itself or the active area is the important factor another plate holder with a circular cut out with a 22.8 mm diameter is manufactured and measured. The diameter of 22.8 mm leads to almost the same active area as for the rectangular cut out. Fig. 10 shows the dissipation curves of both setups with the same active area (rectangular and medium size circular one). The dissipation curve for the circular cut out is different to the rectangular one. Still, the circular cut out results in one additional low frequency peak whereas the rectangular one results in two additional low frequency peaks. Interestingly the frequency of the first peak of both curves occurs at the same frequency, but the dissipation of the circular cut out is much higher which might be caused by the vibration mode of the flexible wall. However, the main peak differs between both measurements. This is caused by the flexible wall and its specific dissipation which is near to the resonators resonance frequency and therefore influences the resonance frequency.

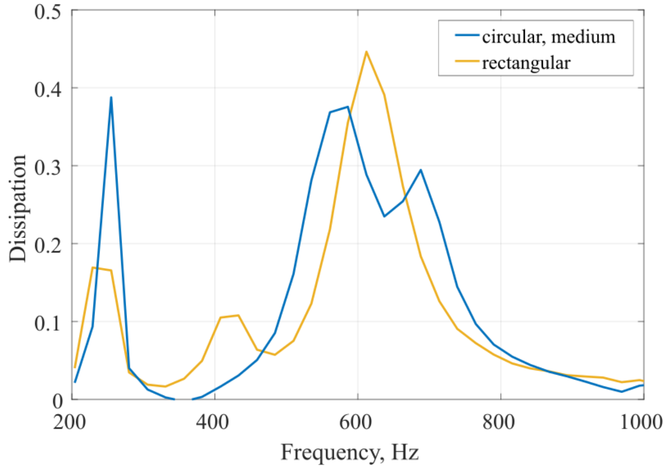


Fig. 10 Dissipation of TPU with 0.3 mm thickness as comparison between a circular cut out and the rectangular cut out with the same active area

The influence of shape and size can be qualitatively predicted by plate theory with an exact calculation being very difficult due to uncertainty of material properties (e.g. Young's modulus, thickness, anisotropy) and boundary conditions (clamped, free or simply supported). Therefore, the extensive experimental investigation is needed to address these effects and provide validation data for modelling.

- **A4: Size of back cavity**

Beside the material, the back cavity size is presumably an important factor for the dissipation. Comparable to the Helmholtz resonator frequency, the additional dissipation's frequency decreases with an increasing back cavity volume (higher number graphs in Fig. 11). It is reasonable to assess the effect not solely in physical dimension of the back cavity depth, but to consider the ration between the volumes of the main and the back cavity. Fig. 11 shows the dependency of the back cavity size, or the ratio to the resonator volume, respectively, on the dissipation. The ratio of zero indicates that no back cavity but a flexible wall is used.

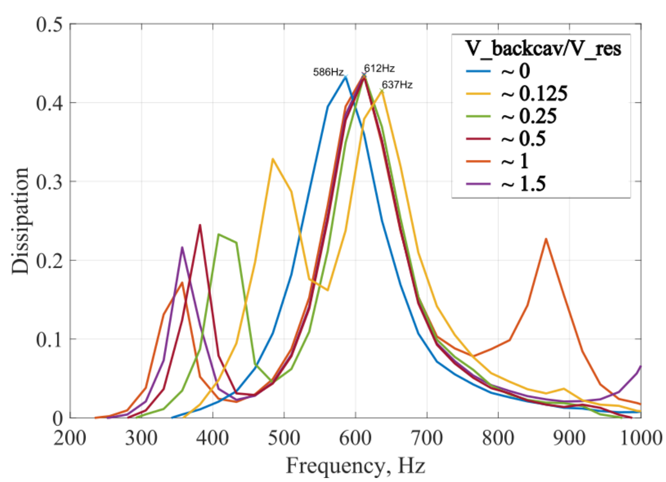


Fig. 11 Dissipation of different volume ratios (back cavity to resonator) for TPU with 0.3 mm thickness and circular cut out

It is visible that the back cavity has almost no influence on the main dissipation peak near 600 Hz resulting from the Helmholtz resonator but it seems to have an influence on the additional dissipation in low frequencies. In general, the smaller the back cavity, the smaller is the gap between the flexible-wall-dependent dissipation peak and the Helmholtz resonator dissipation peak. It seems that the smallest back cavity also has an impact on the Helmholtz resonance frequency. This influence of the flexible wall on the resonator's frequency is already mentioned for the bigger circular cut out. On the other hand, the smaller back cavities also result in higher dissipation peaks which may be due to the fact that they are closer to the Helmholtz resonance. The additional peak over 800 Hz for the measurement where the back cavity is about the same size as the resonator, seems to be dependent on the wavelength. More investigation is needed in order to find out why it does not occur for other geometries. Due to our focus on lower frequencies it is not further investigated yet.

Regarding the goals for the acoustic liner problem such as low frequency and broadband damping, the dependency on back cavity size may prevent a straight-forward optimization. With small back cavities, which reduce the "loss on lined surface", no low frequency tuning with the additional dissipation peak can be obtained. However, the small back cavities lead to a broadband dissipation. On the other hand, if the back cavity is fairly small, the main dissipation peak itself is shifted to lower frequencies. The dissipation at low frequencies is achievable with relatively big back cavities which somehow contradict the desire to make best use of the whole available area for acoustic lining.

- **A5: Number of flexible walls**

The former parts only consider measurements with one flexible wall in the resonator. However, the number of flexible walls might also have an influence on the dissipation. In Fig. 12 the dissipation curves of one resonator with different numbers of flexible walls of same geometry and material is shown. In all cases a circular cut out with a diameter of 15 mm and the TPU material with 0.3 mm thickness is used.

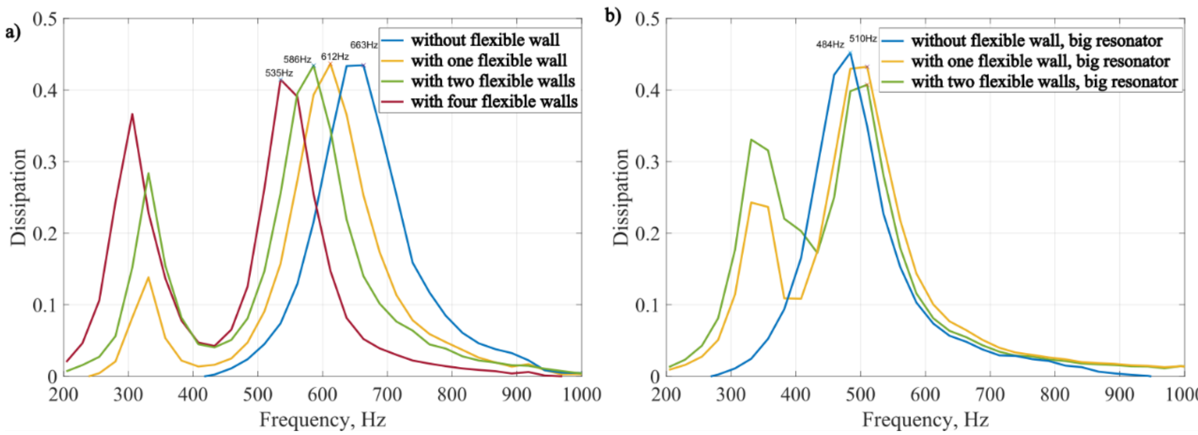


Fig. 12 Comparison of dissipation for different numbers of flexible walls at one resonator with a) increasing resonator volume and b) constant resonator volume

The two setups of Fig. 12 a) and b) are built up with one resonator. For each flexible wall, the volume of the resonator itself increases by 20 % of the reference resonator volume as the one-centimeter thick walls of the resonator cube are partly removed and the flexible wall is put on top of the resonator's structure. For the setup in Fig. 12 b), the same resonator volume is used for all three measurements by removing the resonator walls and installing a backing plate on the resonator's structure.

By using two flexible walls, the flexible-wall-dependent dissipation peak is higher than for only one flexible wall but remains at the same frequency as can be seen in Fig. 12 a). However, there is a kind of linear relationship between one and two flexible walls (the second wall doubles the dissipation compared to one flexible wall) which does not occur when comparing two and four flexible walls. There is also a shift in the resonator frequency for all measurements and in the flexible-wall-dependent dissipation frequency for four flexible walls. The difference in the resonator-based dissipation is caused by the resonator assembly as every flexible wall leads to a larger resonator volume due to the resonator design as mentioned before. The resonance frequency shift can already be checked by using the simple Helmholtz resonance frequency equation.

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{S_0}{V_0\,L}} \tag{1}$$

The Helmholtz resonance frequency (f_0) is dependent on the speed of sound (c), the open area (S_0), the neck length (L) and the resonator volume (V_0). While the environmental conditions in the lab, as well as the face sheet remain the same, the only variable in this setup is the resonator volume. For Fig. 12 a) the voluminal difference between the blue and the green curves is about seven percent whereas the resonance frequency shift is at about four percent, which is in a comparable number of magnitude. When comparing the resonance frequency between the blue and the yellow line, the shift is also in a comparable number of magnitude (18% compared to 13%). The difference can be explained by the measurement technique of single tones at distinct frequencies which may not match exactly to the actual resonance frequency.

By using the same resonator volume for one or two flexible walls, the resonator-based dissipation remains the same, as can be seen in Fig. 12 b). The results suggest that an increasing number of moving walls is beneficial for the dissipation because an increased part of acoustic energy is transformed into mechanic wall movement. Additionally, the resonator's dissipation remains at the same frequency and at almost the same height. Not only the measurements with the constant resonator volume but also a calculation with the simple Helmholtz equation leads to the same magnitude of frequency shift for the different resonator-based dissipation frequencies. However, there is still a difference between the resonator-based dissipation comparing Fig. 12 a) with four flexible walls and Fig. 12 b) which is caused by the different DUCT sides used for the measurements.

All in all, the results demonstrate that the acoustic characteristics of a Helmholtz resonator with flexible walls depend on a variety of variables. By adding a flexible wall, an additional dissipation, mostly at lower frequencies, occurs. The material properties have the highest influence. The Young's modulus and the thickness of the flexible wall have to be comparably small in order to enable an effect of the flexible wall, otherwise the flexible wall is acoustically stiff and reacts like a hard wall. Another effect on the frequency and form of the dissipation curve has the form and/or area of the flexible wall. This needs further investigation with different methods such as vibrometer measurements. The back cavity volume as well as the number of flexible walls also have big influences on the additional dissipation of the flexible wall. In sum multiple big flexible walls with big cavities and a material with a high textural flexibility lead to a low additional dissipation. However, this is in contrast to the requirement in aviation that all additional parts should decrease in space and weight.

B. Measurements with two resonators

In the following sections the measurements with two resonators will be discussed. In order to reduce the required number of measurements, only circular cut outs (15 mm diameter) with flexible walls of TPU in 0.3 mm thickness are used. The rest of the parameters are held constant. The back cavity size is directly and indirectly changed by distance (spacing) of the resonators. To ensure a tight connection, an external fixator is necessary. All other aspects (e.g. orientation of the flexible wall in comparison to the DUCT and the torque for the assembly) are not changed. In a small series of experiments, findings of the single resonator setup (A1) are confirmed also for the two resonators setup. The main effect comparing one and two resonators is the level of dissipation. The more resonators there are, the higher is the dissipation even if the correlation is not linear.

B1: Spacing of two resonators

The number of resonators and also their spacing has an influence on the dissipation. By increasing the distance between the resonators, the dissipation also increases up to a maximum. In Fig. 13 the dissipation curves for some pairs of resonators at distinct distances are shown. Each line stands for a single distance in both plots Fig. 13 a) and b). The parameter d represents the ratio of the distance s and the wavelength λ of the resonance frequency. The distance s is measured between both centers of resonator's face sheet patterns. In order to have comparable distance ratios, the wavelength is based on the resonance frequency of 612 Hz, as this is equal in all measurements with flexible walls regarded in Fig. 13.

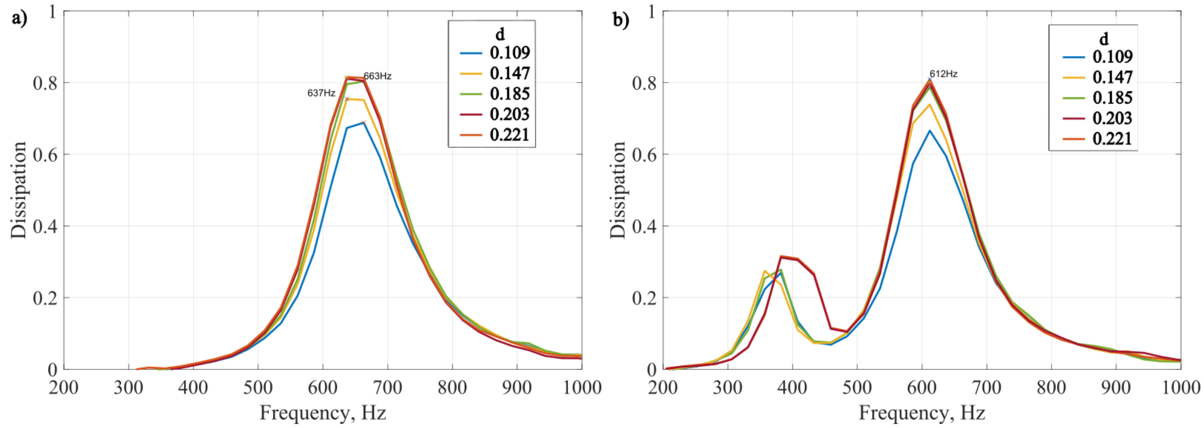


Fig. 13 Dissipation of different resonator's spacing to wavelengths ratios for resonators without a) and with b) flexible walls

Gautam et al. [16] found a dependency on the transmission loss with the wavelength of the resonance frequency relative to the distance between the resonators. He states that at a distance-to-wavelength-ratio of around 0.2 the biggest transmission loss is gained. However, the dependency on the spacing holds true for resonators with and without flexible walls as can be seen in Fig. 13. Compared to the results of Gautam et al. the range of distance to wavelength ratios is a lot smaller in this study due to lower resonance frequencies. However, it has to be noted, that from both studies the ratio at around 0.2 seems to gain the best results regarding the dissipation or transmission loss respectively. This can also be seen in seen in Table 2, where the ratio of wavelength at resonance (λ) and resonator spacing (s) is put in relation to the percentages of dissipation integrals. The percentages are compared to the integral of the biggest distance in this study (s/λ = 0.221). Small differences of two or three percent may be caused by the measurements themselves.

Table 2 Ratio of resonators distances and wavelength in comparison with the integral of dissipation for two resonators without flexible walls

d = s/λ	0.109	0.147	0.185	0.203	0.221
Percentage of integral dissipation in relation to the highest value	85 %	92 %	98 %	97 %	100 %

In the present measurements the highest dissipation already occurs at a distance-to-wavelength-ratio of 0.18. This differs from the findings of Gautam et al because of the smaller ratio steps caused by bigger wavelengths and a bigger resonator and hole pattern respectively.

As the resonator volume slightly changes when adding a flexible wall, the Helmholtz resonance frequency also alters in the two plots of Fig. 13. The differences in resonance frequency in Fig. 13 a) are reasoned by the measured distinct frequencies. The real resonance frequency seems to be around 650 Hz. This also leads to a very high dissipation at s/ λ ≈ 0.18. As can be seen in Fig. 13 b) at s/ λ ≈ 0.2 the additional dissipation of the flexible wall is also higher than for lower ratios. However, this is the same ratio that Gautam et al. also found for the best spacing when comparing the dissipation or transmission loss respectively.

The positive influence of spacing between the resonators shows that a spacing is useful for higher dissipation or transmission loss although it needs space which is often a limiting factor. Regarding the space which is needed for back cavities, this fact might be a chance for the given concept. However, to find an optimum between the effect of spacing and the loss of active liner area will be further investigated.

B2: The interaction between two resonators with flexible walls

Two resonators offer the possibility of different coupling combinations of the resonators. The resonators can be coupled directly, via a direct connection between the two resonators or via flexible walls and back cavities, or they can be uncoupled when the face sheet and the DUCT is the only connection between the resonators. Regarding the direct coupling, there is also the possibility to use either two or three flexible walls. When only two flexible walls are used, the space of the third flexible wall can be used for additional back cavity volume as in the first setup of Fig. 14. Having a look at Fig. 14, where the dissipation for different setups at a specific resonator's distance is plotted, it can be seen, that the coupling mode do not seem to have a big influence on the dissipation.

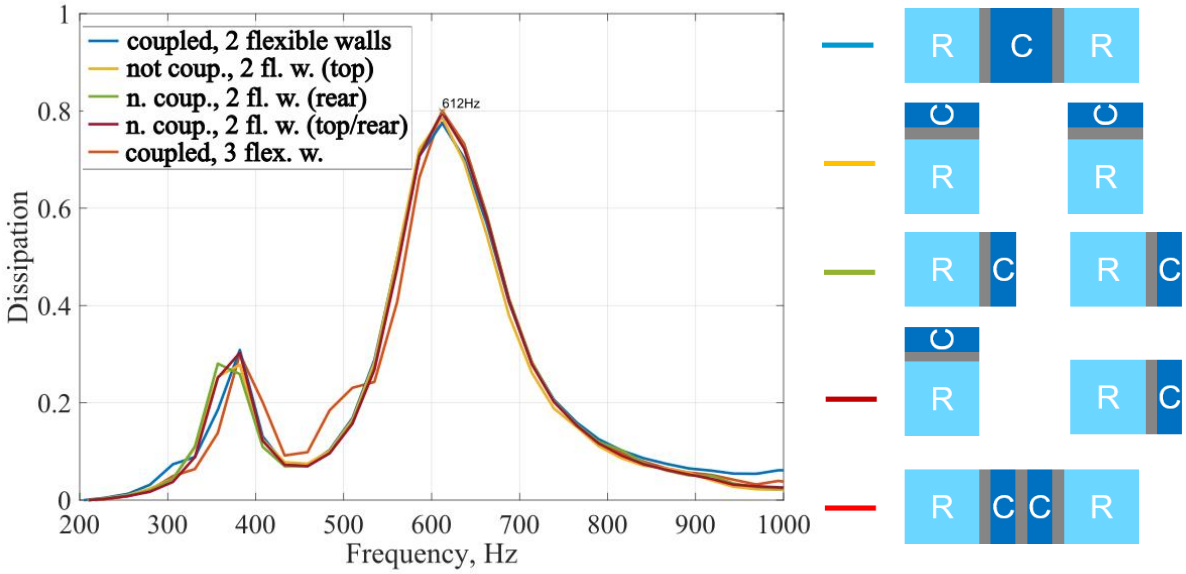


Fig. 14 Comparison of dissipation of coupled and uncoupled resonators and their schematic view at a distance of 104 mm between the resonators

Whether the resonators are coupled or uncoupled has almost no influence on the dissipation. As long as the distance between the resonators as well as the number of resonators and flexible walls remain the same, the dissipation curve is the same in the presented measurements as shown in Fig. 13. This is an unexpected result which could have an influence on the arrangement of active and passive cells in a liner sample. By taking a closer look on the blue dissipation curve for one back cavity between the two resonators, one will see a small difference compared to the other curves at low frequencies. One reason may be the size of the back cavity which is in sum bigger than for all the other measurements presented in Fig. 14. This result shows the same dependency as of the single resonator where a bigger back cavity lead to lower frequency dissipation.

In the measurements with coupled resonators we tested some combinations with a third flexible wall between the two back cavities. This third flexible wall results in a little different dissipation, as can be seen in the comparison of measurements (see Fig. 15). The integral of the dissipation in Fig. 15 a) differs for less than two percent between all three measurements whereas the maximum difference of the dissipation integrals in Fig. 15 b) is at five percent. The differences are in the range of measurement errors which leads to the result that a third flexible wall is not beneficial enough, given the additional implementation effort needed for installation in a real liner.

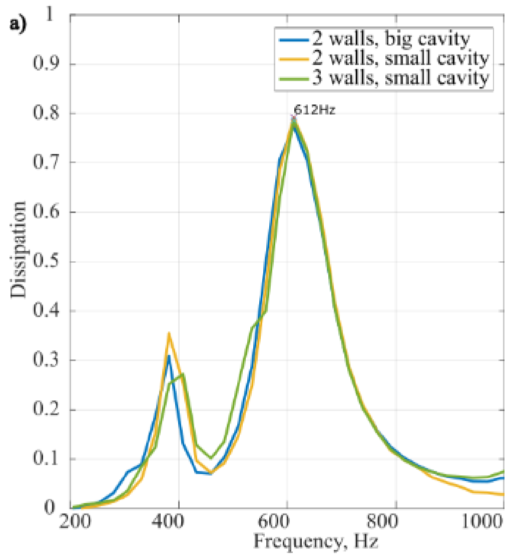


Fig. 15 Comparison in dissipation of coupled resonators with two or three flexible walls with a) 104 mm distance and b) 124 mm distance between the resonators

Summarizing, there is almost no difference in the dissipation by coupling the resonators which is a useful finding for the liner sample geometry. There is no need to couple the cells with each other in order to have a better resonator. This leads to an easier liner design with a better manufacturing process of the liner.

An interesting result only occurs while comparing the results of one resonator to measurements with two resonators. By comparing the green dissipation curve of Fig. 12 b) with all the dissipation curves in Fig. 14 one will see that the low frequency dissipation peak is higher for one resonator with two flexible walls than for two resonators with one flexible wall each. On the other hand, the Helmholtz resonance-based dissipation is much higher for two resonators than for only one. This means that the additional low frequency dissipation does not follow the same rules as the resonator-based dissipation. To find out the reasons, further investigation is needed. However, the information that two flexible walls in one resonator result in a higher dissipation is useful for the liner design.

V. Conclusion and Outlook

A modular resonator setup with multiple flexible walls and resonators is designed in order to investigate the influence of concept parameters on the dissipation of a resonator with a flexible wall. A lot of measurements for different setups are taken. The material has the most influence on the dissipation. In order to reach additional dissipation to the one of the Helmholtz resonator, a material with a low Young's modulus is needed. Moreover, the shape and area of the flexible wall's cut out as well as the back cavity size and the number of flexible walls have an influence on the dissipation. The shape and area have an influence on the number of additional low frequency dissipation peaks whereas a bigger back cavity size shifts these peaks to lower frequencies. A higher dissipation is gained by using more flexible walls in one resonator. The measurements of one and two resonators showed, that the position of the flexible wall only has a small influence on the dissipation. This represents an useful fact for a liner design as the whole depth of the Helmholtz resonator cells can be used when the flexible wall with the back cavity is placed between two resonator cells. Especially for the two resonator measurements, the spacing has a larger influence on the dissipation of the whole system than the coupling combination.

The presented results show the possible effects of flexible walls which need further optimization in order to reach the goals. The two possible optimization goals, high bandwidth and low frequencies, need further investigation and need to face the requirements for low weight and space consumption.

The results of the investigations presented here are used to build up a plane liner sample for further measurements in the DUCT. These will be investigated with and without grazing flow in the future.

In order to use the concept in aviation, the impact of high sound pressure levels and the drainage needed for intakes need further investigation. Finally, a liner barrel should demonstrate the applicability for circular ducts.

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