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LONG ELASTIC OPEN NECK ACOUSTIC RESONATOR FOR WIDE FREQUENCY RANGE

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Passive acoustic liners, used in aeronautic engine nacelles to reduce radiated fan noise, have a Quarter-wavelength behavior. The simplest systems are SDOF-type (Single Degree Of Freedom) and composed of a perforated sheet backed to a honeycomb. So, their acoustic absorption ability is naturally limited to one frequency range around the Helmholtz frequency, and mainly governed by honeycomb thickness. To widen the frequency range of absorption, manufacturers double the concept, called 2DOF (Double Degree Of Freedom), with an internal layer upper another honeycomb. The interaction between both systems is designed to avoid a discontinuity in frequency. One constraint is the limited thickness of global system which reduces the space dedicated to each honeycomb, and can shift the absorption towards higher frequencies. A possible approach could be also to link each perforated layer with hollow tubes introduced in honeycombs, to shift resonance frequencies to lower frequencies by a prolongation of air column lengths. This approach is inspired by a previous concept called LEONAR ("Long Elastic Open Neck Acoustic Resonator), SDOF system in which the total thickness can reach a value lower than $\lambda/30$. The presence of honeycomb on both sides of the internal perforated layer allows also, by tubes crossing the two cavities, to increase the tube length by keeping the liner thickness. The aim of this paper is to describe mathematically the principle of a 2DOF LEONAR, to lead a parametric analysis and to validate experimentally in impedance tube its behavior according to Sound Pressure Level and frequency. Comparisons are achieved with classical 2DOF systems used for aeronautic applications, to show its advantages (absorption in a wide and low frequency range, materials by design, robust modelling with respect to conditions of excitation) and its limitations (manufacturing by 3D printing).

Keywords: Acoustic Impedance, materials by design

1. Introduction

Locally reacting liners, as those used in aeronautical engine nacelles, are generally “sandwich” resonators with a perforated plate linked to a honeycomb material above a rigid plate (called SDOF for Single Degree Of Freedom). Their absorption behavior can be described approximately with the principle of an Helmholtz resonator. The frequency range of absorption is so essentially controlled by the thickness of the honeycomb cavity (with a "Quarter-wavelength" behavior). The small size of holes (mostly from 0,4 to 2 mm according to industrial needs), absorbs the energy (thanks to the acoustic boundary layer applied at the internal walls) when a wave is propagated through the resonant cavity [1,2]. In order to absorb in several frequency bands, different types of SDOF liners can be piled up to constitute 2DOF or 3FOF liners [3]. Nevertheless, their physical law is not suited to an absorption to the lowest frequencies, as needed for future Ultra High Bypass Ratio (UHBR) engines with shorter and thinner nacelles (frequencies around 500 Hz). A possible approach could be to link each perforated layer with hollow tubes introduced in honeycombs, to shift resonance frequencies to lower frequencies by a prolongation of air column lengths. This approach is inspired by a previous concept of SDOF resonator called LEONAR ("Long Elastic Open Neck Acoustic Resonator) [4,5].

This paper describes mathematically the principle of a 2DOF LEONAR and shows, with many experimental and simulated comparisons, their potential in aeronautics for absorption in low frequency band.

2. Description of 2DOF LEONAR

The resonator is composed of a double system with perforated plates, whose holes are connected to hollow flexible tubes, inserted in cavities and opened at the end (Figures 1 and 2). The tubes linked to down plate can be fit flush with the down plate surface (Figure 1 - left) or inserted partly in the higher cavity (Figure 1 – right).

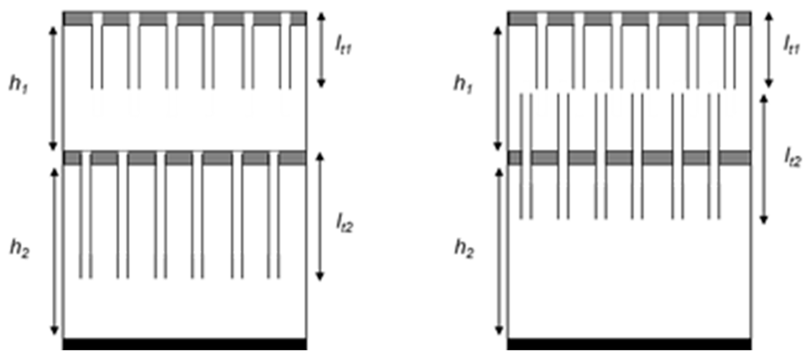


Figure 1: 2D illustration of 2DOF LEONAR with hollow tubes in cavities – down tubes flush with the down plate surface (left) or inserted partly in the higher cavity (right).

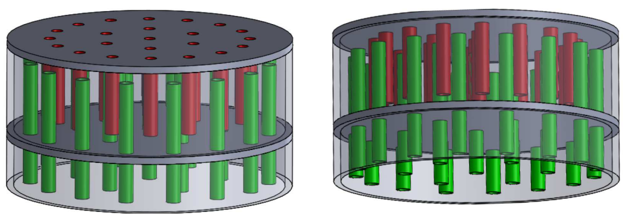


Figure 2: 3D illustration of 2DOF LEONAR with hollow tubes in cylindrical cavities – configuration with down tubes inserted partly in the higher cavity.

The parameters describing the resonator are respecively: the plate porosity σ_p, the inner and outer tube radius r_i and r_e, the tube lengths l_{t1} and l_{t2} and the cavity thicknesses h_1 and h_2.

The propagation of waves along hollow tubes can be shown as a linear combination of "propagational", "thermal" and "viscous" modes [6]. We assume that the wavelength of waves is much larger than the inner diameter of a tube.

To simplify the mathematical description, the theory of sound propagation is shown in narrow channels with plane parallel plates (distance: 2 r_i).

The pressure field in presence of visco-thermal effects is solution of the classical equation:

$$\nabla^2 p + \left(\frac{\omega}{c}\right)^2 p = 0 \qquad (1)$$

and can be expressed as following along channel (direction x):

$$p(x,r) = A\cos(q_r r)\,(e^{iqx} + e^{-iqx}) \tag{2}$$

with q_r the propagation constant in the transverse direction of the channel.

As the associated transverse velocity must vanish at the inner boundaries, the transverse propagation constant (with the assumption of $q_r r_i << 1$) is given by:

$$q_r^2 = \left(\frac{\omega}{c}\right)^2 = -\frac{(\gamma-1)F(k_h r_i) + F(k_v r_i)}{1-F(k_v r_i)} \quad \text{where} \quad F(X) = \frac{\tan(X)}{X} \tag{3}$$

with

- $k_h = \dfrac{1+i}{\delta_h}$ where $\delta_h = \sqrt{\dfrac{2K}{\rho C_p \omega}}$ (thermal boundary layer thickness)
- $k_v = \dfrac{1+i}{\delta_v}$ where $\delta_v = \sqrt{\dfrac{2\mu}{\rho\omega}}$ (viscous boundary layer thickness).

The average axial velocity has the following form:

$$u_x = \frac{Aq}{\omega\rho}\left(1 - F(k_v r_i)\right)\left(e^{iqx} - e^{-iqx}\right). \tag{4}$$

As $q^2 = \left(\dfrac{\omega}{c}\right)^2 - q_r^2$, the complex propagation constant in the axial direction of the channel q is determined simply by:

$$q = \left(\frac{\omega}{c}\right)\sqrt{\frac{1+(\gamma-1)F(k_h r_i)}{1-F(k_v r_i)}} \tag{5}$$

For circular tubes, r_i should be replaced by $r_i/2$ in equations (3), (4) and (5).

Then, one assumes that (Figure 3):

- the continuity of pressure and mass flow between tubes and surrounding cavities is verified at the end of tubes,
- the transmitted waves propagate in rigid cavities, without loss, mainly in the direction of thickness, as for a classical resonator.

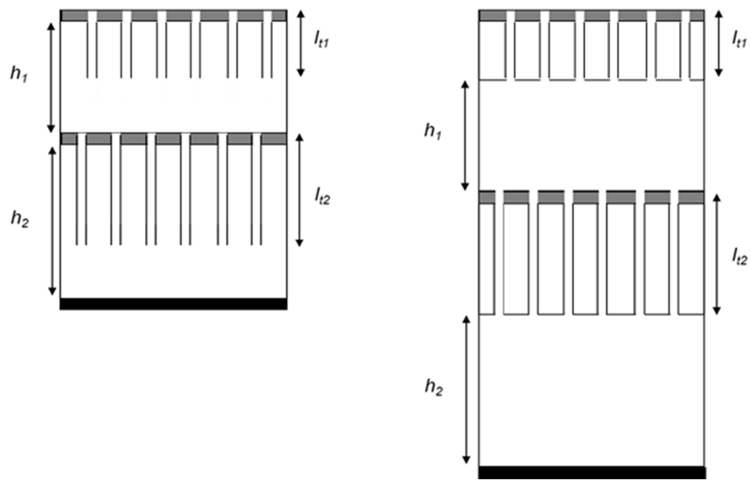


Figure 3: Real (left) and simulated (right) 2DOF resonators

One can define easily the different transfer matrices related to elementary components of 2DOF, as follows:

$$T_{cavity\ 1} = \begin{bmatrix} cos(k\ h_1) & i\rho c\ sin(k\ h_1) \\ i\ sin(k\ h_1)/\rho c & cos(k\ h_1) \end{bmatrix}$$

$$T_{cavity\ 2} = \begin{bmatrix} cos(k\ h_2) & i\rho c\ sin(k\ h_2) \\ i\ sin(k\ h_2)/\rho c & cos(k\ h_2) \end{bmatrix}$$

$$T_{tube\ 1} = \begin{bmatrix} cos(q\ l_{t1}) & i\frac{\rho\omega}{q(1-f_v)}\ sin(q\ l_{t1}) \\ i\frac{q(1-f_v)}{\rho\omega}\ sin(q\ l_{t1}) & cos(q\ l_{t1}) \end{bmatrix}$$

$$T_{tube\ 2} = \begin{bmatrix} cos(q\ l_{t2}) & i\frac{\rho\omega}{q(1-f_v)}\ sin(q\ l_{t2}) \\ i\frac{q(1-f_v)}{\rho\omega}\ sin(q\ l_{t2}) & cos(q\ l_{t2}) \end{bmatrix}$$

$$T_{Tubes/cavity} = \begin{bmatrix} 1 & 0 \\ 0 & 1/\sigma_p \end{bmatrix}$$

$$T_{Cavity/tubes} = \begin{bmatrix} 1 & 0 \\ 0 & \sigma_p \end{bmatrix}$$

(6)

So, $$T_{total} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = T_{tube\ 1} \times T_{Tubes/cavity} \times T_{cavity\ 1} \times T_{Cavity/tubes} \times T_{tubes\ 2} \times T_{Tubes/cavity} \times T_{cavity\ 2} \quad (7)$$

The specific impedance of the structure is given thanks to the plate porosity:

$$\frac{Z_s}{\rho c} = \frac{T_{11}}{T_{21}} \times \frac{1}{\rho c \sigma_p} \quad (8)$$

Classical inductive and resistive end corrections can also be added in specific impedance, i.e, [7], but the effects are relatively negligible for long tubes and low frequencies.

3. Theoretical and experimental study

The validation is led on different 2DOF configurations (Figure 4), i.e. variable cavity lengths and PTFE tubes of variable lengths are specified in Table 1.

The impedance is obtained in an impedance tube equipped with three microphones for pressure measurements (standard measurement method in accordance with [8,9]). On the opposite side of the tube, the loudspeaker generates a broadband random noise propagated in plane waves from 200 to 4,000 Hz.

As this type of tube have a linear behaviour according to the incident acoustic pressure level [4], only one sound pressure level is delivered, that to say 110 dB.

Indeed, non-linearity are due to acoustic vortices around the holes on a plate for a high ratio of " r_i / l_p " (hole radius / plate thickness). So, to increase artificially the plate thickness, by the extension of tubes, prevent the presence of vortices.

Table 1: Characteristics of samples

σ_p (%)	r_i (mm)	r_e (mm)	l_{t1} (mm)	l_{t2} (mm)	h_1 (mm)	h_2 (mm)
4	0.35	0.55	5 10 20	5 10 20	7 12 17 22	7 12 17 22

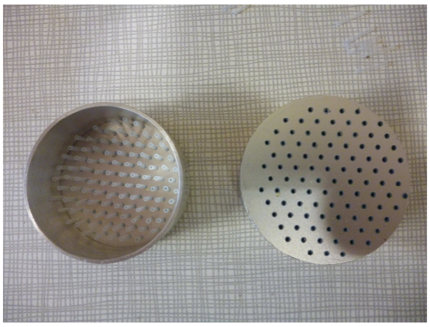


Figure 4: Components of 2DOF LEONAR - perforated plates connected to tubes: view from cavity side (left) / view from opposite side (right)

In Figure 5-a, is shown the absorption coefficient with down tubes flush with the down plate surface, for different values of down cavity thicknesses (12, 17 and 22 mm). One can notice that the behaviour of these 2DOF resonators is relatively well identified by this simple model, that is to say, in the two main frequency ranges of absorption (up to 2600 Hz). Nevertheless, appears a third energetic band whose the physics is not included.

Moreover, for a given pair of single resonators, their respective location (top or down) is an important parameter in medium frequency range (Figure 5-a, Figure 5-b).

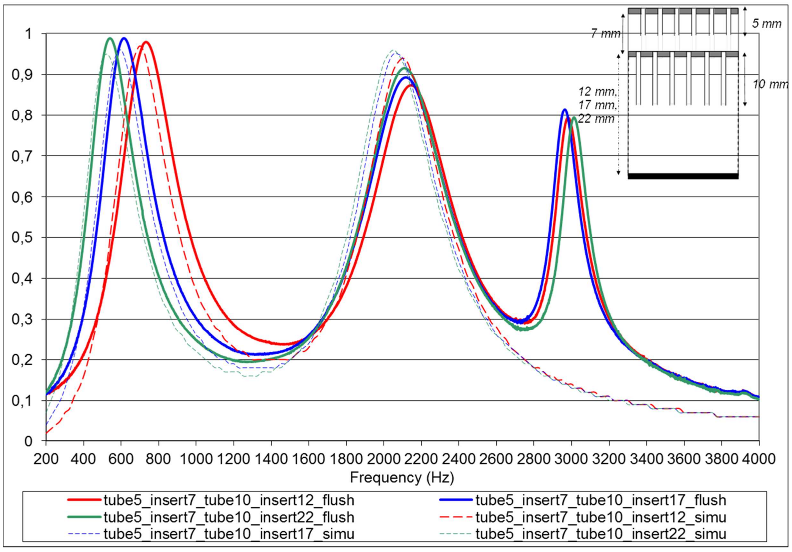
To insert tubes by 5 mm in the higher cavity (Figure 6) has a negligible effect in low and medium frequency range. Nevertheless, discrepancies appear between simulations and experimentations with insertion by 15 mm in the higher cavity of 17 mm (Figure 7). This can be partially explained by interactions between top and down flexible tubes. However, it is noticeable that an insertion has the advantage of allowing for increasing the length of down tubes for a small down cavity length (if required by operating conditions), while providing low frequency bands of absorption. Finally, if tube lengths are inverted for unchanged cavity lengths (Figure 8), resonators with shorter top tubes and longer down tubes (i.e. 10 mm) are preferred to enlarge the frequency range towards higher frequencies.

4. Conclusion

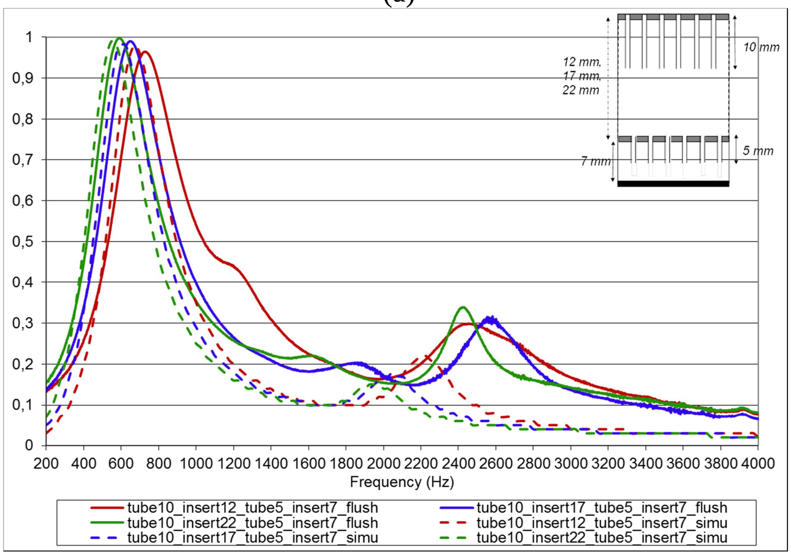
This experimental and theoretical study has shown that application of LEONAR principle to 2DOF resonators offers the advantage to produce absorption in several frequency bands, as for classical 2DOF resonators. Moreover, the introduction of tubes in two cavities of a conventional resonator generates a significant shift of the frequency range of absorption towards lower frequencies, thus by a prolongation of air column length. So, the thickness can reach a value lower than $\lambda/20$ (compared to $\lambda/4$).

Despite the simplicity of theoretical approach, the absorption coefficient (or the impedance) can be determined with dimensional parameters, which permits optimisations processes (in particular because the behaviour is linear according to sound pressure level).

Finally, while these particular materials have been manufactured manually, their architectural design is suited to 3D printing by stereolithography, and so can be applied to an industrial application as the aeronautics [5].



(a)



(b)

Figure 5: Comparison between simulated and experimental absorption coefficients with down tubes flush to the down plate surface – (a) configuration 1 (b) configuration 2

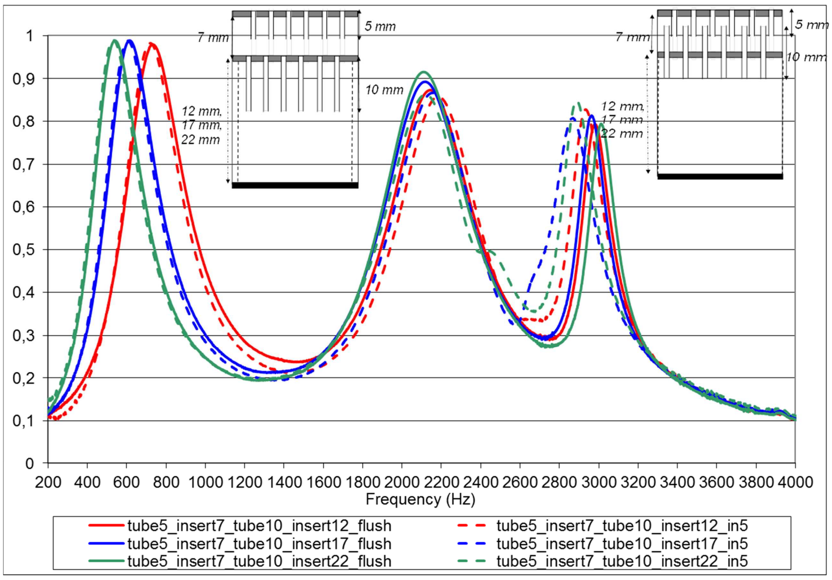
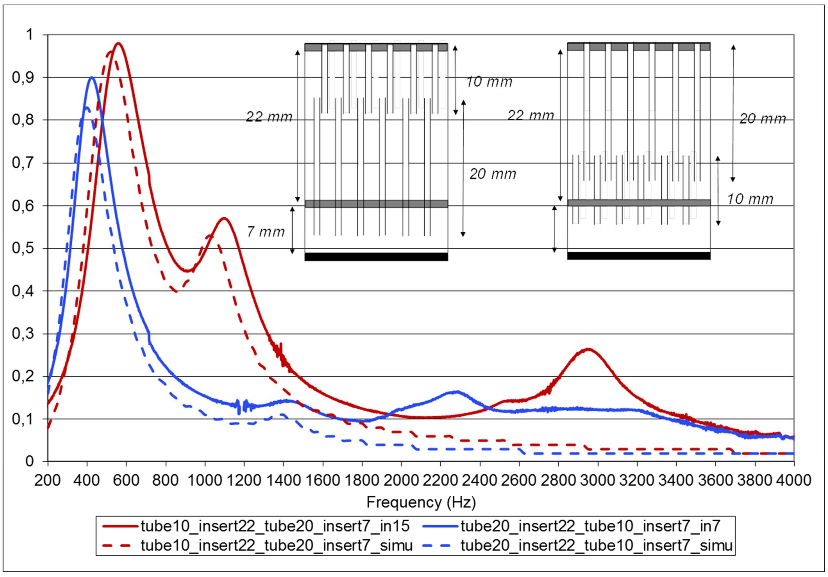
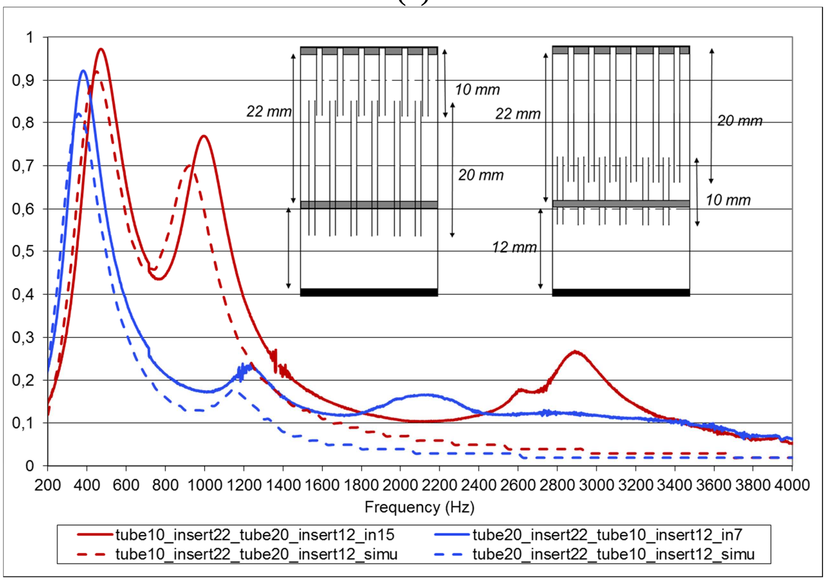


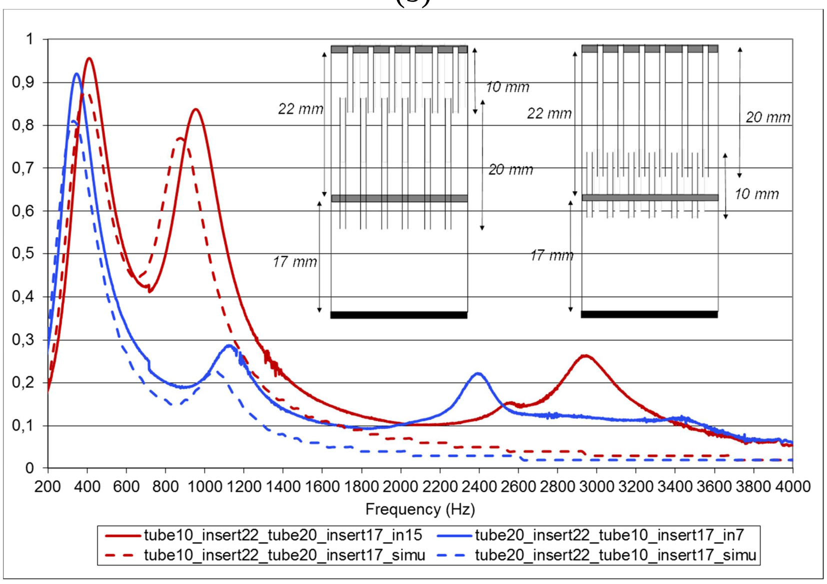
Figure 6: Comparison between experimental absorption coefficients with down tubes flush to the down plate surface (left) or inserted by 5 mm in the higher cavity (right).



(a)



(b)



(c)

Figure 8: Comparison between experimental absorption coefficients with down tubes flush to inserted by 15 mm in the higher cavity (right).

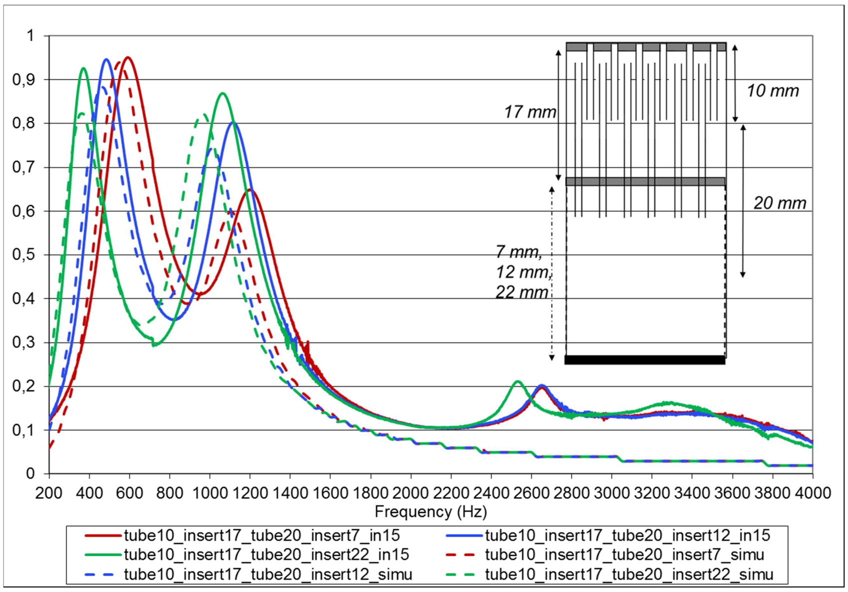


Figure 7: Comparison between experimental absorption coefficients with down tubes flush to inserted by 15 mm in the higher cavity (right).

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