



# IMPLEMENTATION OF A TUNING SYSTEM FOR HELMHOLTZ RESONATOR ARRAYS IN A HVAC DUCT

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## **Abstract**

Onsite tuning is mandatory to utilize Helmholtz resonators for HVAC ducts. However, no tuning device or general-use system is yet available, and engineers have thus been avoiding the use of such resonators. The objective of this study is to develop a tuning system for resonator arrays for HVAC ducts. We employed the cavity volume, resonator neck resistance and neck open area as control parameters to tune the resonance frequency, resonance sharpness and sound dissipation factor, respectively. To control the cavity volume, resistance and neck open area, respectively, a cylinder with a screwed shaft, a spiral spring with adjustable gaps between the spring plates, and a camera aperture were used. These were controlled by individual stepper motors, which were driven by signals supplied by a PC. An experimental resonator array tuning system composed of six prototype tuning devices was built and installed in a section of a 250-mm diameter duct. The eighteen parameters of the six resonators were tuned successively through a feedback approach allowing the transmitted traveling plane wave to reach its target spectrum with reasonable precision. When a resonator tuner was inactive at its target resonance frequency, this target resonance frequency was switched to that of the next inactive tuner.

**Keywords:** Helmholtz resonator, tuning device, spiral spring, HVAC duct.

## **1 Introduction**

For sound control in HVAC (Heating Ventilating and Air Conditioning) ducts, Helmholtz resonators have outstanding advantages such as lower flow disturbance, smaller space requirement, higher sound dissipation ability for lower audible frequency, and precision frequency control.

However, onsite tuning is mandatory to utilize Helmholtz resonators for HVAC ducts. Unfortunately, no tuning device or general-use system is available, and for this reason engineers have been avoiding the use of such resonators. The objective of this study is to develop a tuning system for resonator arrays as a dissipative rather than a reactive element in HVAC ducts. We employed the cavity volume, resonator neck resistance and neck open area as the control parameters of the resonator to allow tuning of the resonance frequency, resonance sharpness and sound dissipation factor, respectively. To control the cavity volume, resistance and neck open area, respectively, a cylinder with a screwed shaft, a spiral spring with adjustable gaps between the spring plates, and a camera aperture were used. These were adjusted by individual stepper motors, which were driven by signals from a PC to control the sound pressure of the transmitted wave. Each tuner was replaced by a resonator with its control parameters tuned. A resonator array tuning system composed of several prototype tuning devices was build and tested for 250-mm diameter HVAC ducts.

## 2 Design parameters of Helmholtz resonator

### 2.1 Acoustic impedance

Helmholtz resonators are used almost exclusively in the side-branch configuration when they are applied to HVAC ducts, as shown in Figure – 1. We consider a sound in a duct with a frequency in the lower audible region, represented by a one-dimensional wave, i.e., a fundamental mode, traveling along the axial direction and having a wavefront which is uniform across the duct cross section.

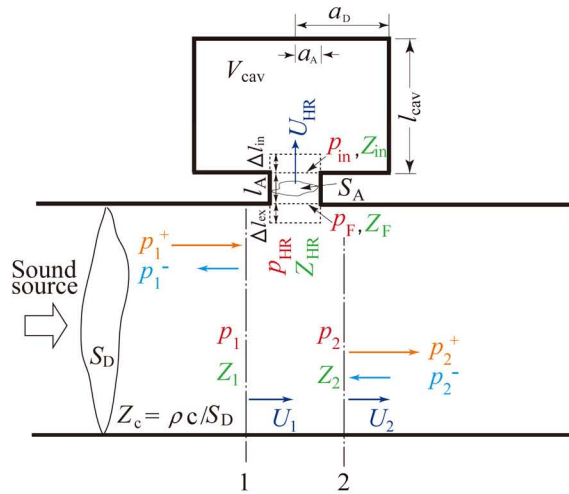


Figure – 1 Plane wave model for a duct with a side-branch Helmholtz resonator.

#### 2.1.1 Interior acoustic impedance

For a resonator, the full wave analyses use the acoustic impedance of the resonator interior,  $Z_F$ , which is expressed as

$$Z_F = p_F / U_{HR} \quad \text{and} \quad Z_F = R_A + j l_A \omega \rho / S_A + Z_{in}, \quad (1) \quad (2)$$

where  $U_{HR}$  denotes the complex amplitude of the volume velocity flowing into the resonator, and  $p_F$  is the complex pressure amplitude of the external-side surface of the resonator aperture.  $R_A$ ,  $S_A$  and  $l_A$  are denoted as the acoustic resistance, the sectional open area and the length, respectively, of the resonator aperture.  $\omega$  is the radian frequency and  $\rho$  is the density of the air.  $Z_{in}$  is the acoustic impedance of the interior-side surface of the aperture and is represented as

$$Z_{in} = p_{in} / U_{HR} = R_{in} + jX_{in} , \quad (3)$$

where  $p_{in}$  is the complex pressure amplitude of the interior-side surface of the resonator aperture, and  $R_{in}$  and  $X_{in}$  denote the acoustic resistance and reactance of the interior of the cavity, respectively.  $X_{in}$  is represented as

$$X_{in} = \Delta l_{in} \omega \rho / S_A - \rho c^2 / \omega V_{cav} , \quad (4)$$

where  $V_{cav}$  is the volume of the cavity and  $\Delta l_{in}$  is the interior-orifice correction, i.e., the mass-end correction for the interior side of the aperture.  $R_A$  and  $R_{in}$  are related to the specific resistances  $r_A$  and  $r_{in}$ , respectively, as

$$R_A = r_A / S_A \text{ and } R_{in} = r_{in} / S_A \quad (5) \quad (6)$$

For a stiff wall cavity  $R_A \gg R_{in}$ , and  $R_A$  will thus be used instead of  $R_A + R_{in}$  from now on.

### 2.1.2 Total acoustic impedance

On the other hand, in one-dimensional wave analysis the total acoustic impedance of a resonator,  $Z_{HR}$ , has been used.  $Z_{HR}$  is expressed as

$$Z_{HR} = p_{HR} / U_{HR} \text{ and } p_{HR} = p_F + Z_{rad} U_{HR} \quad (7) \quad (8)$$

where  $p_{HR}$  stands for the complex pressure amplitude at the junction of the duct with the resonator when  $U_{HR} = 0$ ,  $Z_{rad}$  denotes the acoustic radiation impedance composed of the radiation resistance and reactance,  $R_{rad}$  and  $X_{rad}$  respectively, i.e.,

$$Z_{rad} = R_{rad} + jX_{rad} , \quad (9)$$

Denoting  $\Delta l_{ex}$  as the external-orifice correction, i.e. the mass-end correction for the external side of the aperture, and using the relationships

$$X_{rad} = \omega \rho \Delta l_{ex} / S_A , \quad (10)$$

$$Z_{\text{HR}} = Z_{\text{F}} + Z_{\text{rad}}, \quad R_{\text{HR}} = R_{\text{A}} + R_{\text{rad}} \quad \text{and} \quad r_{\text{HR}} = r_{\text{A}} + r_{\text{rad}} \quad (11) \quad (12)$$

we have

$$Z_{\text{HR}} = R_{\text{HR}} + j \left\{ \omega \rho l_{\text{e}} / S_{\text{A}} - \rho c^2 / \omega V_{\text{cav}} \right\}, \quad (13)$$

where  $c$  is the speed of sound in air. The equivalent neck length  $l_{\text{e}}$  is introduced as

$$l_{\text{e}} = l_{\text{A}} + \Delta l_{\text{ex}} + \Delta l_{\text{in}}. \quad (14)$$

The external-orifice correction  $\Delta l_{\text{ex}}$  for side-branch resonator apertures,  $\Delta l_{\text{ex}}^{(\text{side})}$ , is given in the literature [1]. However the interior mass-end correction  $\Delta l_{\text{in}}$  for Helmholtz resonator apertures has not been reported. Figure – 2 shows the interior-orifice correction  $\Delta l_{\text{in}}$  obtained by using eq. (4) and conducting numerical simulations for  $X_{\text{in}}$  [1].

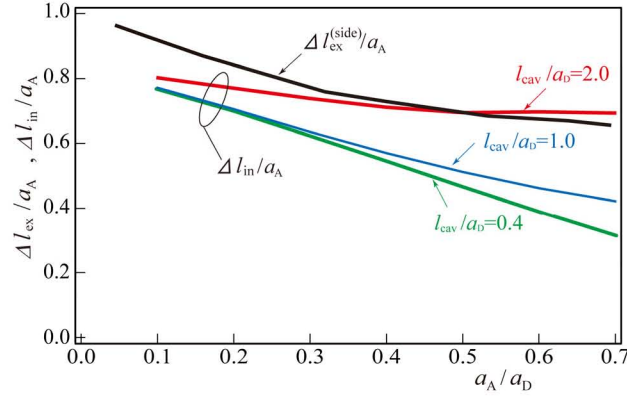


Figure – 2 Interior-orifice correction  $\Delta l_{\text{in}}$ .

## 2.2 Acoustic properties of the resonator

The acoustic properties to be tuned are the resonance frequency  $f_{\text{res}}$ , the quality factor  $Q$  and the acoustic dissipation factor  $\delta_{\text{HR}}$ .

The resonance frequency  $f_{\text{res}}$  and the quality factor  $Q$ , respectively, can be written as

$$f_{\text{res}} = (c / 2\pi) \sqrt{S_{\text{A}} / l_{\text{e}} V_{\text{cav}}}, \quad (15)$$

and

$$Q = 2\pi f_{\text{res}} \rho l_{\text{e}} / r_{\text{HR}}. \quad (16)$$

Taking Eq. (12) into account,  $Q$  is largely dependent on  $r_{\text{A}}$ .

The acoustic dissipation factor  $\delta_{\text{HR}}$ , i.e., the ratio of the sound power dissipated by the resonator to the incident sound power, is represented as

$$\delta_{\text{HR}} = 4R_{\text{A}}^* / \left| R_{\text{A}}^* + R_{\text{A}}^* Z_{\text{c}} / Z_2 + 1 \right|^2, \quad (17)$$

where  $Z_{\text{c}} = \rho c / S_{\text{D}}$  denotes the characteristic impedance of a duct with a cross-sectional area  $S_{\text{D}}$ , and  $Z_2$  is the acoustic impedance of the duct connected downwards. A non-dimensional resistance

$$R_{\text{A}}^* = R_{\text{A}} / Z_{\text{c}} = r_{\text{A}} / S_{\text{A}} Z_{\text{c}}, \quad (18)$$

is then introduced.

When the duct has an anechoic termination, i.e.,  $Z_2 = Z_{\text{c}}$ , the sound dissipation factor reduces to

$$\delta_{\text{HR}} = R_{\text{A}}^* / \{ (R_{\text{A}}^* + 1/2)^2 + (X_{\text{HR}} / Z_{\text{c}})^2 \}. \quad (19)$$

At  $R_{\text{A}}^* = 1/2$ , the dissipation factor takes its maximum value  $\delta_{\text{HR}} = 1/2$ , the transmission factor (ratio of the sound power transmitted downward in the duct to the incident sound power) is 1/4 and the reflection factor (ratio of the sound power reflected back upward in the duct to the incident sound power) is 1/4. This implies that the transmission loss for one resonator section is 6dB (at the utmost) when a Helmholtz resonator is used as a sound dissipation element (as in this case) rather than a reactive one.

### 2.3 Control parameters of the resonator

Based on Eqs. (15), (16) and (17), we employed the cavity volume  $V_{\text{cav}}$ , resonator neck resistance  $r_{\text{A}}$  and neck open area  $S_{\text{A}}$  as the control parameters for the resonator, respectively, for tuning the resonance frequency  $f_{\text{res}}$ , quality factor  $Q$  and sound dissipation factor  $\delta_{\text{HR}}$ . For tuning  $Q$  we had the choice of using either  $l_{\text{e}}$  or  $r_{\text{A}}$  according to Eq. (16). We abandoned attempts to use  $l_{\text{e}}$  because  $r_{\text{A}}$  has a tendency to be proportional to  $l_{\text{e}}$ , and the tuning sensitivity using  $l_{\text{e}}$  is not promising.

## 3 Prototype resonator tuner

A prototype resonator tuning device was fabricated as shown in Figure – 3. To control the cavity volume  $V_{\text{cav}}$ , resistance  $r_{\text{A}}$  and neck open area  $S_{\text{A}}$ , respectively, a cylinder with a screwed shaft, a spiral spring with an adjustable gap between the spring plate, and a camera aperture were used. These were controlled by individual stepper motors, which were driven by signals from a PC.

### 3.1 Cavity volume control

To control the cavity volume  $V_{\text{cav}}$ , a cylinder with a screwed shaft was used. To rotate the shaft, a stepper motor was attached. The cavity volume  $V_{\text{cav}}$  could be controlled from 100 cm<sup>3</sup> to 4,000 cm<sup>3</sup> using cylinders of different diameters.

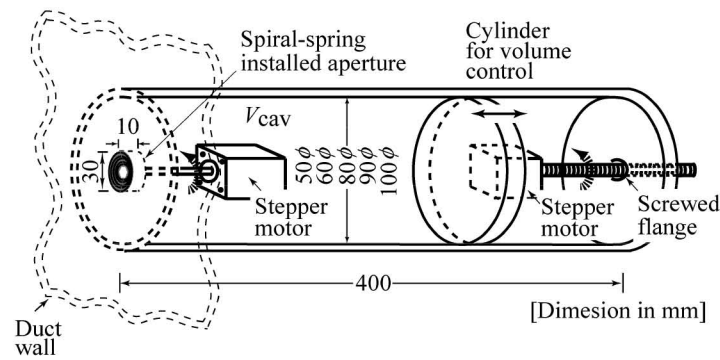


Figure – 3 Prototype resonator tuner.

### 3.2 Resistance control

To control the resistance  $r_A$ , a spiral spring [2] was used as shown in Photo – 1. In the resonator neck a spiral spring was mounted with a camera aperture as shown in Figure – 4. The gap  $b$  between the plates of the spiral spring was adjusted by rotating the core shaft attached to one end of the spring using its own stepper motor. The gap  $b$  could be controlled from 0.3 mm to 2.6 mm, allowing the resistance  $r_A$  to be controlled from  $4 \rho c$  to  $60 \rho c$  as shown in Figure – 5.

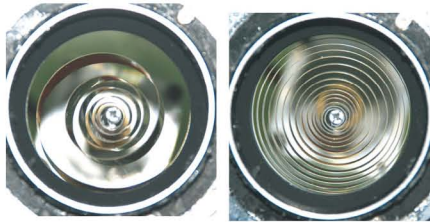


Photo – 1 Spiral spring for resistance control.

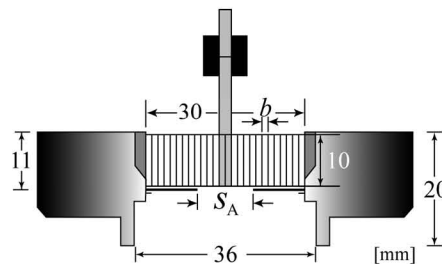


Figure – 4 Spiral spring embedded aperture.

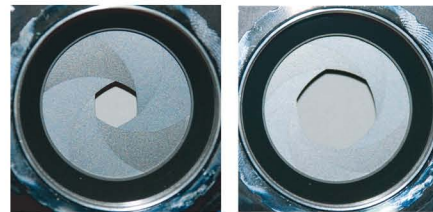
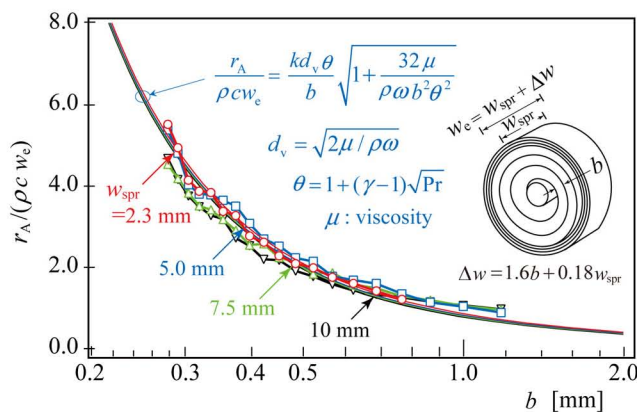


Photo – 2 Open area controllable aperture

Figure – 5 Resistance  $r_A$  control by spring gap  $b$ .

### 3.3 Open area control

The camera aperture mentioned above was used to control the neck open area as shown in Photo – 2 and Figure – 4. The aperture blades were rotated by their own stepper motor, and the area  $S_A$  could be controlled from  $4 \text{ mm}^2$  to  $660 \text{ mm}^2$ .

## 4 Tuning experiments

The prototype resonator tuning system was tested in HVAC ducts as shown in Photo – 3. First, the effectiveness of a dissipative resonator array was studied in a duct with anechoic termination. Subsequently, the effectiveness of the tuning system for resonator arrays was studied in a duct with reflective termination.



Photo – 3 Prototype tuners attached to a HVAC duct.

### 4.1 Tuning procedure

Tuning is conducted to reduce the traveling wave pressure of the downward duct,  $p_{\text{down}}^+$ , to some required level. The traveling wave pressures in the forward and backward directions,  $p_{\text{down}}^+$  and  $p_{\text{down}}^-$ , were measured by using the two-microphone method. Tuning is carried out through a trial-and-error method to reach the desired target. The procedure used is primarily as follows: (1) find frequency regions with large excess pressure; (2) attach as many tuners as needed to independently reduce the excess pressure of each of these frequency regions. For each tuner, the initial value of  $r_A$  is set to its maximum value in order to minimize sudden change in the pressure  $p_{\text{down}}^+$  when the tuner is installed.  $S_A$  is set to  $S_A = 2r_A / Z_c$  to maximize  $\delta_{\text{HR}}$  as mentioned in regard to Eq. (19), and  $V_{\text{cav}}$  is set to  $V_{\text{cav}} = (c / 2\pi f_{\text{res}})^2 l_e / S_A$  from Eq. (15) to match  $f_{\text{res}}$  to the frequency region of large excess pressure; (3) while checking  $p_{\text{down}}^+$  and  $\delta_{\text{HR}}$  (by Eq. (17) and the  $Z_2$  value obtained from the  $p_{\text{down}}^{+/-}$  measurement), slowly vary  $r_A$ ,  $S_A$  and  $V_{\text{cav}}$  for the tuner with the largest excess pressure. If a tuner is found to be ineffective, exchange the assigned frequency for that of the next ineffective tuner at a different sectional location, as will be mentioned in Section 4.3.2. Repeat these steps until the target is reached.

### 4.2 Tuning in a duct with anechoic termination

The effectiveness of the dissipative resonator array system was studied in a HVAC duct with low reflective termination (very close to anechoic termination) as shown in Figure – 6.



A tuning system consisting of 3 prototype controllable resonator devices was used. Figure – 7 and Table – 1 show the transmitted sound  $p_{\text{down}}^+$  and the dissipation factor  $\delta_{\text{HR}}$ , and the states of the parameters at specific points in the tuning process. Compared to the theoretical result described in Section 2.2, the reduction of the transmitted sound  $p_{\text{down}}^+$  is around 4 dB instead of 6 dB. The dissipation factor  $\delta_{\text{HR}}$ , varies from 0.3 to 0.5 instead of 0.5. Taking into account the incomplete anechoic termination, these results imply the potential effectiveness of the dissipative resonator array system.

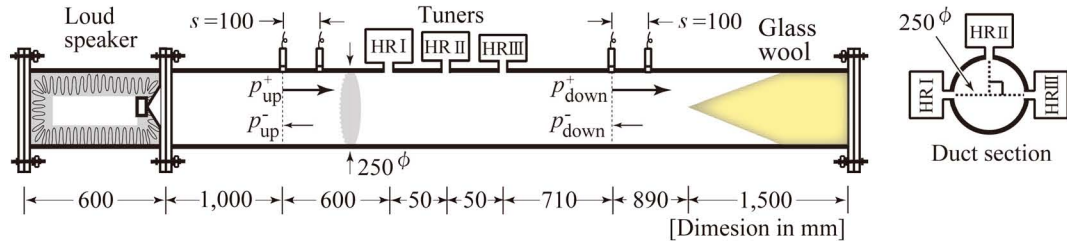
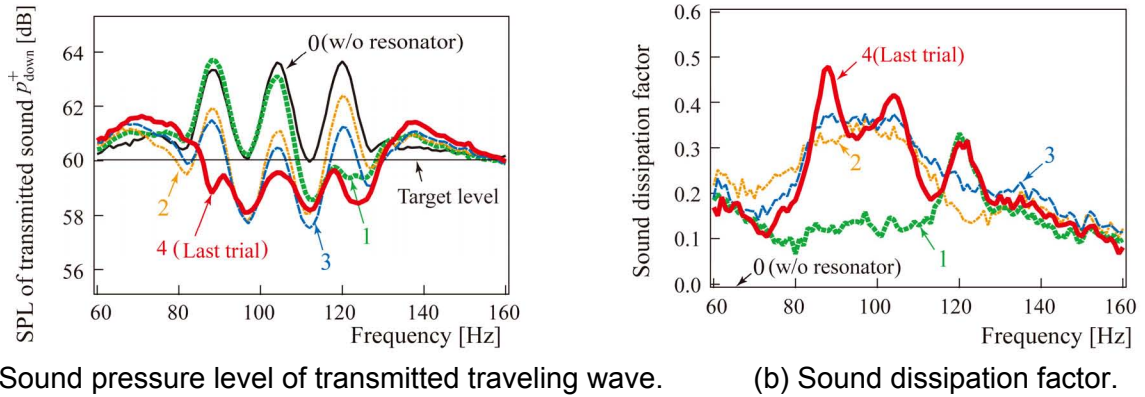


Figure – 6 Dissipative resonator array system in a HVAC duct with low reflective termination.



(a) Sound pressure level of transmitted traveling wave.

(b) Sound dissipation factor.

Figure – 7 Sound pressure of transmitted traveling wave  $p_{\text{down}}^+$  and the dissipation factor  $\delta_{\text{HR}}$ .

Table – 1 States of the parameters at specific points in the tuning process.

Trial	Tuner I							Tuner II							Tuner III						
	$S_A$ (mm <sup>2</sup> )	$\delta$	$b$ (mm)	$r_{\text{HR}}^*$	$Q$	$V_{\text{cav}}$ (l)	$f_{\text{res}}$ (Hz)	$S_A$ (mm <sup>2</sup> )	$\delta$	$b$ (mm)	$r_{\text{HR}}^*$	$Q$	$V_{\text{cav}}$ (l)	$f_{\text{res}}$ (Hz)	$S_A$ (mm <sup>2</sup> )	$\delta$	$b$ (mm)	$r_{\text{HR}}^*$	$Q$	$V_{\text{cav}}$ (l)	$f_{\text{res}}$ (Hz)
0	w/o resonator							w/o resonator							w/o resonator						
1	4	—	0.3	—	—	2.61	—	4	—	0.3	—	—	2.37	—	660	0.33	2.6	1.4	9.2	1.36	120
2	220	0.31	1.1	8.9	2.1	2.42	88	220	0.35	1.1	8.9	2.1	1.81	104	220	0.16	1.1	8.9	2.1	1.36	120
3	410	0.37	1.1	2.5	5.3	2.42	88	410	0.37	1.1	2.5	5.5	1.81	104	410	0.23	1.1	2.5	5.5	1.36	120
4	660	0.48	2.6	1.4	9.3	2.42	88	660	0.42	2.6	1.4	9.3	1.81	104	660	0.31	2.6	1.4	9.3	1.36	120

### 4.3 Tuning in a duct of reactive termination

#### 4.3.1 Tuning of the resonator array

The effectiveness of the resonator array tuning system was studied in a duct with reflective termination as shown in Figure – 8. A tuning system consisting of 5 prototype controllable resonator devices was applied to control the transmitted sound  $p_{\text{down}}^+$ . Figure – 9 and Table – 2 show the transmitted sound  $p_{\text{down}}^+$  and the dissipation factor  $\delta_{\text{HR}}$ , and the states of the parameters at specific points in the tuning process.



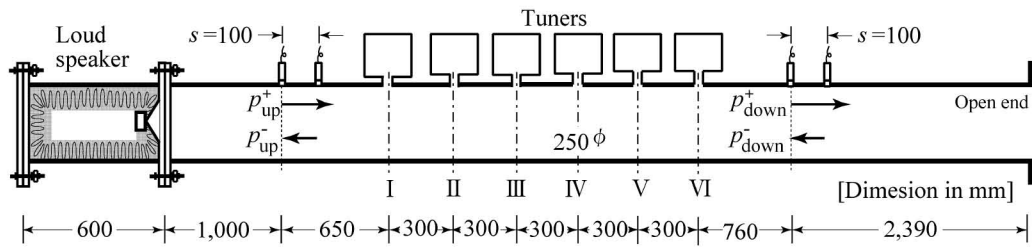
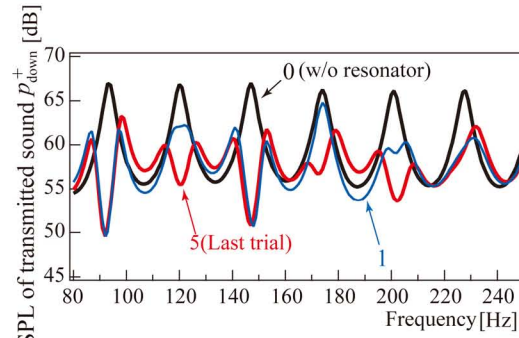
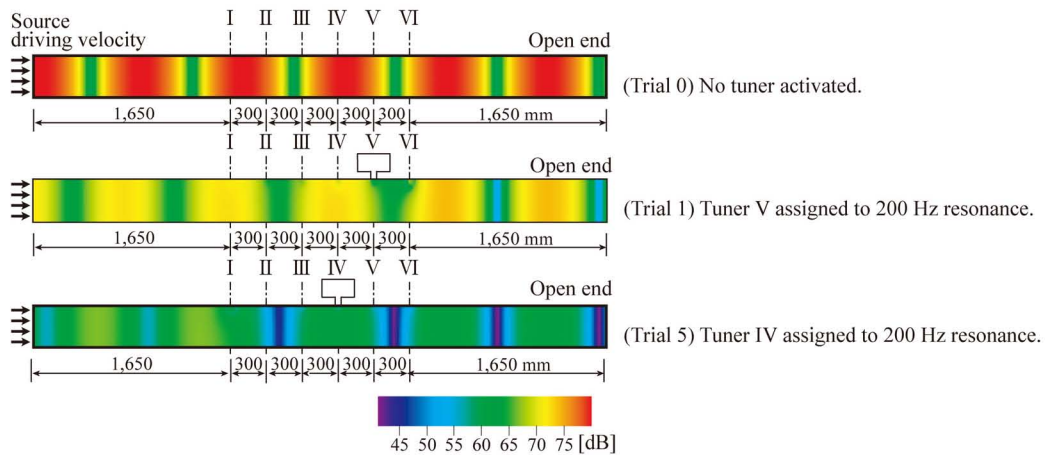


Figure – 8 Resonator array tuning system in a duct of reflective termination.

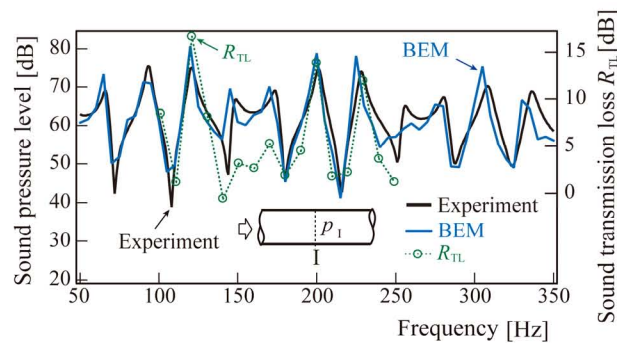
Table – 2 States of the parameters at specific points in the tuning process.

Trial	Resonance frequency [Hz]					
	I	II	III	IV	V	VI
0	w/o resonator					
1	95	120	150	175	200	230
2	*	:	:	200	175	:
3	*	:	175	:	120	:
4	*	175	95	:	:	:
5	230	95	150	200	120	175

\* Omitted from figure 9


 Figure – 9 Transmitted sound  $p_{\text{down}}^+$  and dissipation factor  $\delta_{\text{HR}}$ .


(a) Tuner assigned to 200 Hz resonance and sound pressure distribution in the duct.



(b) Sound pressure spectra at tuner position I and maximum sound transmission losses when resonance frequencies of tuner I are varied at 10 Hz intervals from 100 to 250 Hz.

Figure – 10 Inactive tuner position and pressure distribution in the duct.

Inactive resonators were found in the tuning steps. For instance at trial step 1, the tuners II, IV and V respectively assigned to the 120, 175 and 200 Hz regions, are rather inactive. In the subsequent steps, detecting two tuners that are the most ineffective, the frequency regions assigned to these two were switched with each other, and at step 5 every tuner has become active in its assigned frequency region.

#### 4.3.2 Inactive resonator location

The inactive tuner phenomenon was studied by BEM and experiments. The velocity of the loudspeaker diaphragm was measured by B&K laser-Doppler velocimetry and used for the BEM simulation. It was found that a tuner becomes inactive when its position corresponds to a pressure node caused by interference between the incident and reflected waves at the resonance frequency of the tuner, as shown in Figure – 10. Switching inactive tuners can be done more effectively if we utilize the sound pressure distribution given from the traveling-wave pressures  $p_{\text{down}}^{+/-}$  monitored by the microphone pair located in the downward duct.

## 5 Conclusions

To realize widespread use of Helmholtz resonator arrays with HVAC ducts, a prototype resonator tuning system has been constructed. Each tuning device in the system consists of a volume control cylinder, resistance control spiral-spring mounted neck and area control aperture, for tuning the resonance frequency, sharpness and sound dissipation factor, respectively.

The prototype tuner system was tested by conducting experiments on HVAC ducts. Consequently, it was confirmed that tuning can be effectively carried out by the use of stepper motors and PC modulated feedback signals from the transmitted traveling sound pressure in the HVAC ducts.

In some instances in the tuning process, some tuners do not work effectively at their assigned resonance frequency regions. By conducting experiments and numerical simulations, it was found that this phenomenon takes place when the tuners are positioned at pressure nodes. In that case, the resonance frequency assigned to the most inactive tuner was switched to that assigned to the next inactive tuner.

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