About 3D Cavity Resonance

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Abstract

Research on automobile whistling and suction sounds has been conducted in the past. For cavity resonance, a type of whistling sound, the cavity resonance frequency has been determined using Rossiter's empirical equation. Therefore, we limited our study to the three-dimensional case and clarified the physical phenomena that arise by solving a set of partial differential equations that explain the phenomenon. As a result, we were able to determine the frequency at which resonance increases, taking into account three-dimensional space. Finally, we were able to confirm the conditions under which resonance increases through numerical calculations.

Nomenclature

L_x, L_y, L_z: Size of the hole in the x, y, and z directions.

ρ, c: Air density and air sound speed

ω: Angular frequency

f_x: Frequency obtained from Rossiter's formula

f_{xr}, f_y, f_z: Resonance frequencies in the x, y, and z directions

k: Wavenumber

t: Time

j: Imaginary unit

U, U_{vx}: Mainstream air velocity and vortex (vorticity) velocity

κ: Ratio of vortex (vorticity) velocity to mainstream air velocity

ϕ: Empirical coefficient for phase lag

M: Mach number

ζ: Vorticity

α: Efficiency of conversion from vorticity to sound pressure (dimension: L^2)

β: Efficiency of conversion from sound pressure to vorticity (dimension: $\mathrm{L}^2\mathrm{M}^{-1}\mathrm{T}^1$)

$\delta(x)$: Dirac delta function

$\delta'(x)$: Differential of Dirac delta function

$H(x)$: Heaviside step function

$u(x,y,z,t), v(x,y,z,t), w(x,y,z,t)$: Velocity in the x, y, and z directions

1. Introduction

In the past, research has been conducted on the whistling and suction sounds of automobiles (Calvo, Diaz, & San Roman, 2005) (Chien-Hsiung, Lung-Ming , Chang-Hsien , Yen-Loung , & Jik-Chang , 2009) (George, 1990) (Jagtiani, 1972) (Jung & Oh, 1995) (Münder & Carbon, 2022) (Oettle & Sims-Williams, 2017) (Qatu, Abdelhamid, Pang, & Sheng, 2009) (Wang, Chen, & Zhang, 2021) (Zhang, Meng, Li, & Zheng, 2022). Cavity resonance is a type of whistling sound. In cavity resonance, the cavity resonance frequency has traditionally been determined using Rossiter formula, an empirical formula. Therefore, for cavity resonance in the three-dimensional case, we will clarify the physical phenomena that arise by solving the set of partial differential equations that explain the phenomenon. Finally, we will examine the conditions under which resonance increases in numerical calculations.

These will be discussed below.

2. About 3D Cavity Resonance

2.1. Vorticity Movement Equation

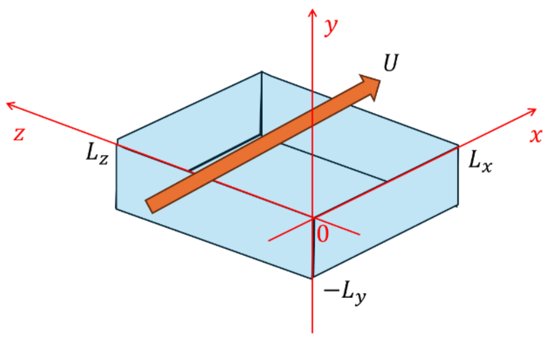

Fig. 1 3-Dimensional Box with Hole

Fig. 1 shows a box with a hole. Here, the conventional definitions of cavity resonance and cavity resonance frequency are given below.

Definition :

When air is flowing at velocity U and there is a hole, a vortex moves from the upstream end to the downstream end of the hole. This vortex collides with the downstream end, generating sound. This generated sound then moves from the downstream end to the upstream end. Sound is a change accompanied by particle velocity, and this particle velocity then collides with the upstream end, generating another vortex. This series of phenomena is defined as "cavity resonance." Furthermore, the reciprocal of the time from when a vortex moves and generates sound until another vortex is generated is defined as the "cavity resonance frequency."

Based on this definition, we derive the differential equation representing cavity resonance, limited to three dimension. First, the movement equation of vorticity $\zeta_z(x,y,z,t)$ is expressed by the following equation. However, the viscosity term is ignored. Furthermore, $\zeta_z(x,y,z,t)$ is the vorticity around the z-axis.

$$\frac{\partial \zeta_z}{\partial t} + U_{vx}\frac{\partial \zeta_z}{\partial x} = 0 \tag{1}$$

2.2. Powell's Equation

Next, we will find the relationship between sound pressure and vorticity.

Powell's equation is the relationship between sound pressure and vorticity. Expressed in three dimension, Powell's equation is given by the following:

$$\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - \left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2}\right)$$
$$= \alpha\rho \sin\left(\frac{\pi z}{L_z}\right)[\zeta_z(L_x,0,z,t)u(L_x,0,z,t)\delta'(x-L_x)\delta(y)$$
$$-\zeta_z(L_x,0,z,t)v(L_x,0,z,t)\delta(x-L_x)\delta'(y)] \tag{2}$$

2.3. Initial Conditions

The initial condition for the velocity in the x-direction is given below:

$$u(x, y \geq 0, 0) = U \tag{3}$$

The initial condition for the velocity in the y-direction is given below:

$$v(x,y,0) = 0 \tag{4}z$$

The initial condition for the velocity in the z-direction is given below:

$$w(x,y,z,0) = 0 \tag{5}$$

The initial condition for the sound pressure is given below:

$$p(x,y,0) = 0 \tag{6}$$

The initial condition for the time derivative of the sound pressure is given below:

$$\left.\frac{\partial p}{\partial t}\right|_{t=0} = 0 \tag{7}$$

2.4. Boundary Conditions

We need to find the boundary conditions under which the velocity of the returned particles changes to vorticity. These are given by the following equation:

$$\zeta(0,0,0 \le z \le L_z, t) = -\beta_x \left.\frac{\partial p}{\partial x}\right|_{(x=0,y=0,t=t)} \tag{8}$$

Furthermore, assuming that sound pressure is completely reflected at the bottom of the box and becomes zero at the open end, the following conditions hold true.

$$\left.\frac{\partial p}{\partial x}\right|_{y=-L_y} = 0 \tag{9}$$

Furthermore, assuming that the sound pressure is completely reflected by the front and back walls, the following conditions hold true.

$$\left.\frac{\partial p}{\partial x}\right|_{x=0,-L_y \le y \le 0} = 0 \tag{10}$$

$$\left.\frac{\partial p}{\partial x}\right|_{x=L_H,-L_y \le y \le 0} = 0 \tag{11}$$

Furthermore, assuming that the sound pressure is completely reflected by the left and right walls, the following conditions hold true.

$$\left.\frac{\partial p}{\partial z}\right|_{z=0,-L_y \le y \le 0} = 0 \tag{12}$$

$$\left.\frac{\partial p}{\partial z}\right|_{z=L_z,-L_y \le y \le 0} = 0 \tag{13}$$

3. Resonance Frequency of a Three-Dimensional Cavity Resonance

3.1. Solution to the Vorticity Transfer Equation

We derive the resonance frequency of a two-dimensional cavity resonance. First, we solve equation (1). The solution when the boundary condition is $\zeta(0,t)$ is given by the following equation:

$$\zeta_z(x,y,z,t) = \zeta_z\left(0,0,z,t-\frac{x}{U_{vx}}\right) \tag{14}$$

3.2. Sound Pressure Equation Using Green's Function Derived from Powell's Equation

Next, we solve Powell's equation (2). This can be obtained using the Green's function in the following form. First, the Green's function is given by the following equation.

$$G(x,y,z,t|x',y',z',\tau) = \frac{c}{4\pi r}\delta(c(t-\tau)-r) \tag{15}$$

Here, the following equation holds true.

$$r = \sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2} \tag{16}$$

From equations (2) and (15), the following equation is obtained.

$$p(x,y,z,t) = \sum_{n=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \left[-\int_0^1 P_{n,m=0,k}(t) d\tilde{z} + \int_0^1 P_{n,m=1,k}(t) d\tilde{z} \right] \tag{17}$$

Here, the following equation holds true.

$$P_{n,m,k}(t) = \frac{\alpha \rho L_x L_y}{4\pi r_{n,m,k}} \left[\frac{1}{c} \frac{\partial}{\partial t} \{ \Phi_{n,m,k}(\tau_{n,m,k}) \} + \frac{1}{r_{n,m,k}} \{ \Phi_{n,m,k}(\tau_{n,m,k}) \} \right] \tag{18}$$

$$\tau_{n,m,k} = t - \frac{r_{n,m,k}}{c} \tag{19}$$

$$\Phi_{n,m,k}(\tau) = \sin(\pi \tilde{z})\, \zeta_z(L_x, 0, \tilde{z}L_z, \tau_{n,m,k})$$
$$\times \left\{ \frac{u(L_x, 0, \tilde{z}L_z, \tau_{n,m,k}) \cdot (x - (2n+1)L_x) - (-1)^{n+k} \cdot v(L_H, 0, \tilde{z}L_z, \tau_{n,m,k}) \cdot (y - Y_m)}{c^2 (t - \tau_{n,m,k})^2 - r_{n,m,k}^2} \right\} \tag{20}$$

$$r_{n,m,k} = \sqrt{(x-(2n+1)L_x)^2 + (y - Y_m)^2 + (\tilde{z}L_z - 2kL_z)^2} \tag{21}$$

$$Y_0 = 0, Y_1 = -2L_y \tag{22}$$

3.3. Frequency in the Mainstream Air Velocity Direction

Consider the frequency in the main stream air velocity direction. The time it takes for vorticity to propagate downstream is $\frac{L_H}{U_{vx}}$, and the time it takes for the sound to return upstream is $\frac{L_H}{c}$. Here, the phase synchronization condition is assumed to be: "Let T_x be the period of the sound produced (frequency is $f_x = \frac{1}{T_x}$). The total time taken for one cycle, $\frac{L_H}{U_{vx}} + \frac{L_H}{c}$, is equal to an integer multiple (n_x times) of the sound period, taking into account the fluid-induced generation delay (phase difference ϕ)." In this case, the following equation holds:

$$\left(n_x - \frac{\phi}{2\pi}\right) T_x = \frac{L_H}{U_{vx}} + \frac{L_H}{c}$$

$$\frac{\left(n_x - \frac{\phi}{2\pi}\right)}{f_x} = \frac{L_H}{U_{vx}} + \frac{L_H}{c}$$

$$f_x = \frac{\left(n_x - \frac{\phi}{2\pi}\right)}{\frac{L_H}{U_{vx}} + \frac{L_H}{c}} \tag{23}$$

Finally, setting $U_{vx} = \kappa U$, we obtain the following equation. This is Rossiter formula.

$$f_x = \frac{U}{L_H} \frac{\left(n_x - \frac{\phi}{2\pi}\right)}{\left(\frac{1}{\kappa} + \frac{U}{c}\right)} \tag{24}$$

3.4. y-Direction Resonance Frequency

The basic formula for the y-direction resonance frequency f_y of an open-end and closed-end tube in stationary space is as follows:

$$f_y = \frac{(2n_y - 1) \cdot c}{4L_y} \tag{25}$$

3.5. x-Direction and z-Direction Resonance Frequency

The basic formula for the x-direction resonance frequency f_{xr} of a closed tube in stationary space is as follows:

$$f_{xr} = \frac{n_{xr} \cdot c}{2L_x} \tag{26}$$

The resonance frequency in the z direction can be considered in the same way as the resonance frequency in the x direction and is given by the following equation.

$$\therefore f_z = \frac{n_z \cdot c}{2L_z} \tag{27}$$

3.6. Three-Dimensional Resonant Frequencies

The three-dimensional resonance frequency f_{total} is given by the following equation:

$$f_{total} = \sqrt{\left(\frac{n_{xr} \cdot c}{2L_x}\right)^2 + \left(\frac{(2n_y - 1) \cdot c}{4L_y}\right)^2 + \left(\frac{n_z \cdot c}{2L_z}\right)^2} \tag{28}$$

The sound pressure increases at this resonance frequency f_{total}.

3.7. Sound Pressure at a Position Outside the Sound Source ($x \geq L_x$)

We will now discuss the sound pressure at a position outside the sound source ($x \geq L_x$). As before, it can be calculated using the following equation.

$$p(x, y, z, t) = -\int_0^1 \frac{\alpha\rho}{4\pi r_{3D}(\tilde{z})} \{\frac{1}{c}\frac{\partial}{\partial t}\Phi_{3D}(x, y, \tilde{z}, \tau_{3D}) + \frac{1}{r_{3D}(z')}[\Phi_{3D}(x, y, \tilde{z}, \tau_{3D})]\} d\tilde{z} \tag{29}$$

Here, the following equation holds.

$$r_{3D}(\tilde{z}) = \sqrt{(x - L_x)^2 + y^2 + (z - \tilde{z}L_z)^2} \tag{30}$$

$$\tau_{3D} = t - \frac{r_{3D}(\tilde{z})}{c} \tag{31}$$

$$\Phi_{3D}(x, y, \tilde{z}, \tau_{3D}) =$$
$$(u(L_x, 0, \tilde{z}L_z, t) \cdot (x - L_x) - v(L_x, 0, \tilde{z}L_z, \tau_{3D}) \cdot y) \sin(\pi\tilde{z})\, \zeta_z(L_x, 0, \tilde{z}L_z, \tau_{3D}) \tag{32}$$

4. Numerical Calculations

The results were confirmed by numerical calculation. The values used are shown in Table 1 below.

Furthermore, for $\frac{\partial p}{\partial x}$ and $v(L_x, 0, z, t)$, it was assumed that vortices were continuously generated at the upstream end at a Rossiter formula primary frequency of 9.6 (Hz), and that this vortex mass was continuously excited at the downstream end as $v(L_x, 0, z, t)$ at the same Rossiter formula primary frequency of 9.6 (Hz). Therefore, the following equation is continuously used during the numerical calculation. Here, $f_{x,1}$ is the Rossiter formula primary frequency of 9.6 (Hz).

$$\frac{\partial p}{\partial x} = \sin(2\pi f_{x,1} t) \tag{33}$$

$$v(L_x, 0, z, t) = \frac{1}{2} \sin\left(\frac{\pi z}{L_z}\right) \sin(2\pi f_{x,1} t) \tag{34}$$

Table 1 Parameter and Value

Parameter	Value
ρ	1.225(kg/m^3)
c	340.0(m/s)
U	34.0(m/s)
κ	0.6
α	1(m^2)
β_x	0.01(m^{2}s/kg)
ϕ	$\frac{\pi}{2}$
L_x	1.5(m)
L_y	0.7(m)
L_z	1.3(m)

The numerical calculation results are shown in Fig. 2. The observation position was

$(x, y, z) = (0.01, 0.01, 0.01)$ near the origin. The top graph shows the time-series waveform of sound pressure, and the bottom graph shows the frequency characteristics of sound pressure.

The time-series waveform of the sound pressure in Fig. 2 shows a peak occurring almost exclusively at the fundamental frequency f_x. This indicates—as evidenced by the frequency characteristics in Fig. 2—that because the analytical solution (Eqation. (17)) involves integration with respect to $\tilde{z}$, the sound source terms distributed along the line $x = L_x, y = 0, 0 \le z \le L_z$ cancel each other out before reaching the vicinity of the origin (0.01, 0.01, 0.01), resulting in the virtual absence of peaks at frequencies other than f_x.

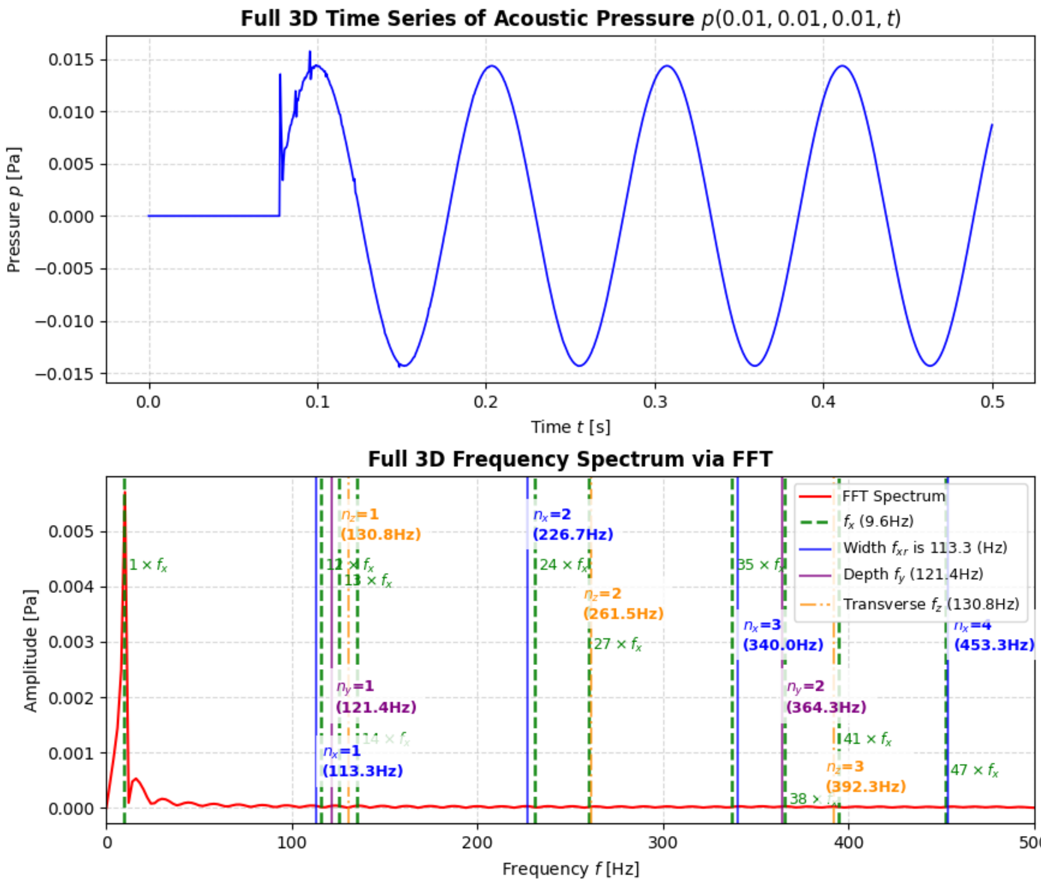

Fig. 2 Numerical Calculation Results

Next, we calculate the sound pressure for $x \ge L_x$. The results are shown in Fig. 3. The observation position was $(x, y, z) = (2.0, 0.5, 0.6)$. The top graph shows the time-series waveform of the sound pressure, and the bottom graph shows the frequency response of the sound pressure.

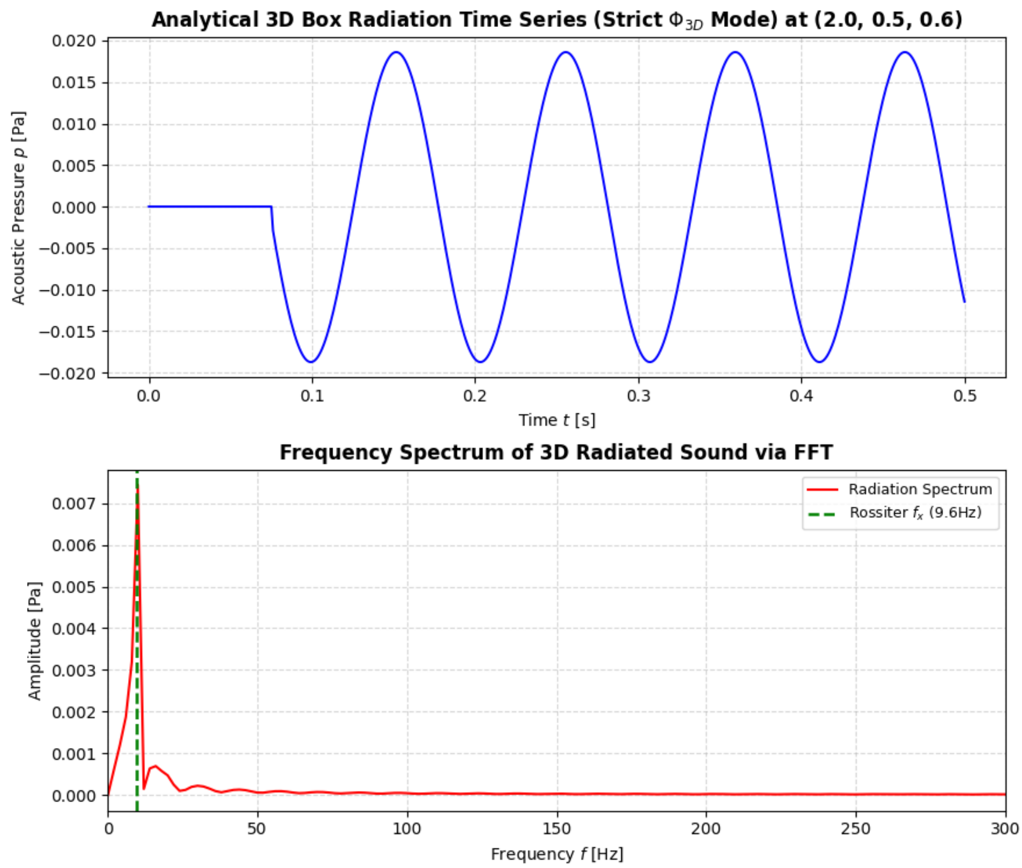

Fig. 3 Numerical Calculation Result ($(x, y, z) = (2.0, 0.5, 0.6)$)

Looking at the top graph in Fig. 3, we can see that time is required for the sound to reach the source. Also, from the frequency response below, a peak at 9.6 (Hz) appears, corresponding to the first frequency of Rossiter formula f_x. That is, for $x \geq L_x$, the sound has a frequency component at the first frequency of Rossiter formula f_x, which is the frequency of forced oscillation.

Next, Fig. 4 presents the numerical calculation results for $U = 1132.3$ (m/s), with the observation point set near the origin at $(x, y, z) = (0.01, 0.01, 0.01)$. The time-series waveforms and frequency characteristics reveal that the fundamental frequency of f_x and the fundamental resonance frequency of f_{xr} coincide and that the sound generated is louder than that shown in Fig. 2; in other words, a lock-in phenomenon is occurring. No significant peaks are observed for f_y or f_z. Furthermore, sound pressures on the order of 10^8 (Pa) are not generated. This suggests a balance between the energy of the sound generated by the source terms (distributed along $x = L_x, y = 0, 0 \leq z \leq L_z$) and the energy of the sound dissipating outward into the external space as spherical waves; the generated sound energy does not become dominant. Although a sound pressure of 4.5 (Pa) appears at the moment sound generation begins, this is attributed to the fact that energy has not yet dissipated from the source terms into the external space. Subsequently, the sound amplitude settles to approximately 2 (Pa) due to mutual cancellation effects and the dissipation of sound energy into the external space.

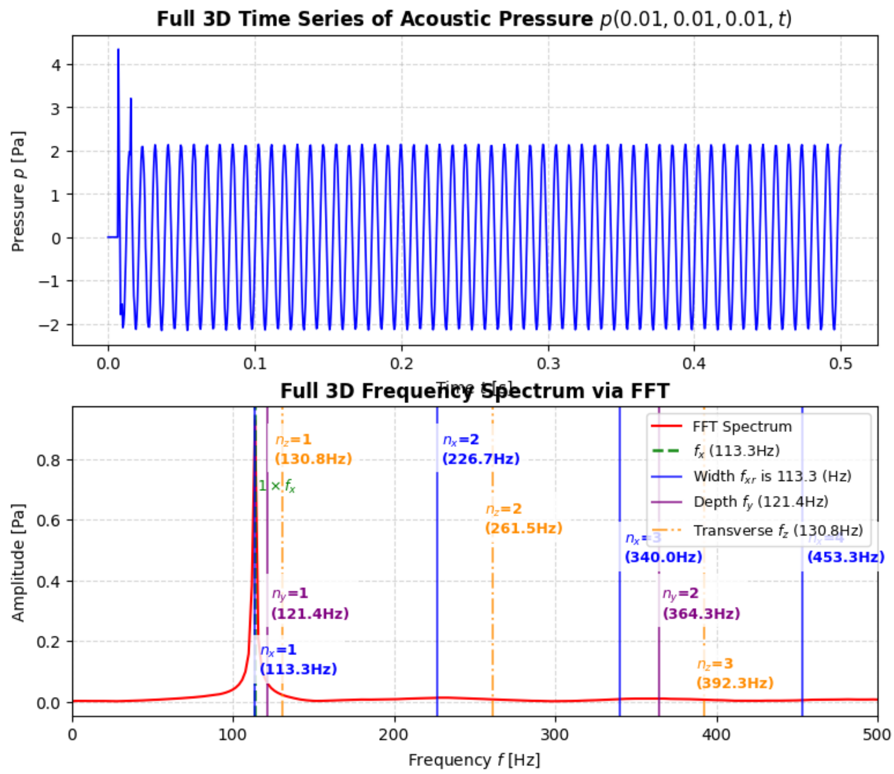

Fig. 4 Numerical Calculation Result ($U = 1132.3$(m/s))

Next, Fig. 5 shows the numerical calculation results for 1250.9 (m/s), with the observation point set at $(x, y, z) = (0.01, 0.01, 0.01)$ near the origin. The first-order resonant frequency of f_x lies at 117.0 Hz—a frequency situated between the first-order resonant frequencies of f_{xr} and f_y—and its amplitude is approximately 0.5 (Pa) greater than that of f_x shown in Fig. 4. Consequently, no significant peaks appear for f_{xr}, f_y, or f_z. The graphs of the time-series waveforms and frequency characteristics reveal that a phenomenon similar to the one discussed in Fig. 4 is occurring.

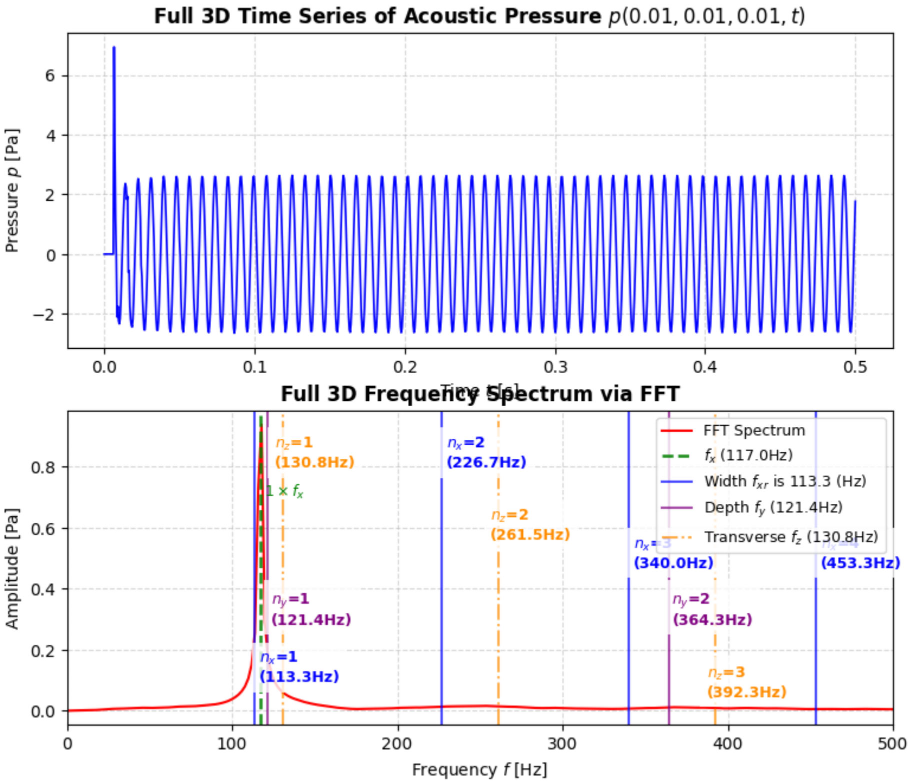

Fig. 5 Numerical Calculation Result (U = 1250.9(m/s))

Next, Fig. 6 shows the numerical calculation results for $U = 1415.5$ (m/s), with the observation point set at $(x, y, z) = (0.01, 0.01, 0.01)$ near the origin. A peak appears where the fundamental frequency of f_x and the fundamental resonant frequency of f_y coincide, and the amplitude is approximately 1 (Pa) greater than that of f_x in Fig. 4. As before, no significant peaks appear for f_{xr} or f_z. The graphs of the time-series waveforms and frequency characteristics reveal that a phenomenon similar to the one discussed in Fig. 4 is occurring.

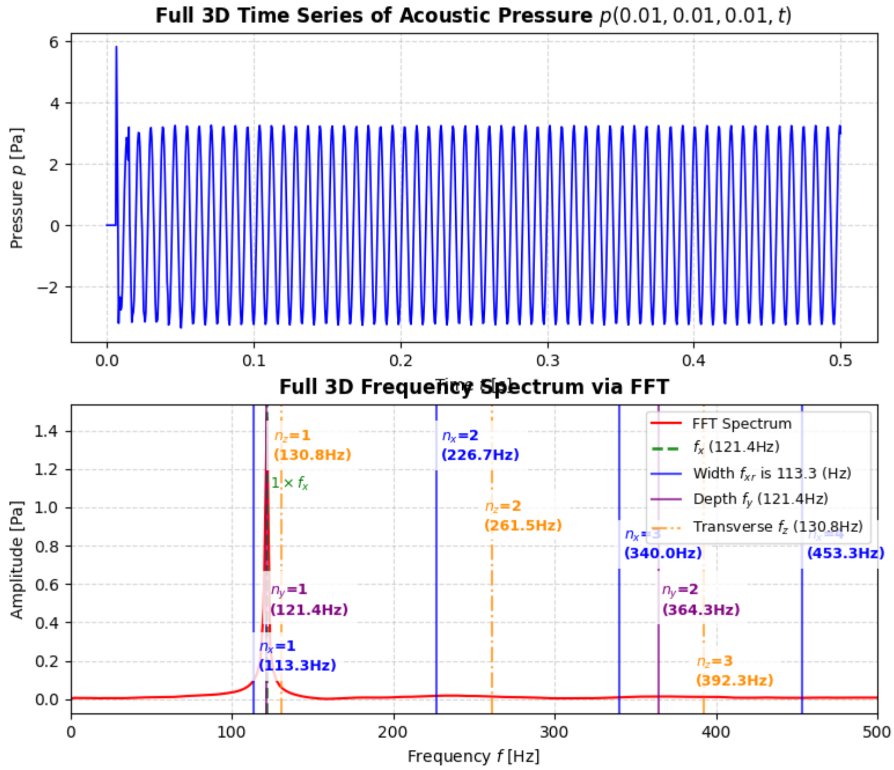

Fig. 6 Numerical Calculation Result (U = 1415.5(m/s))

Finally, Fig. 7 shows the numerical calculation result for $U = 1890.8$ (m/s), with the observation point set at $(x, y, z) = (0.01, 0.01, 0.01)$, near the origin. A peak appears where the fundamental frequency of f_x coincides with the fundamental resonance frequency of f_z, and the amplitude is approximately 3 Pa greater than that of f_x in Fig. 4. As before, no large peaks appear for f_{xr} or f_y. The graphs of the time-series waveforms and frequency characteristics reveal that a phenomenon similar to the one discussed in Fig. 4 is occurring.

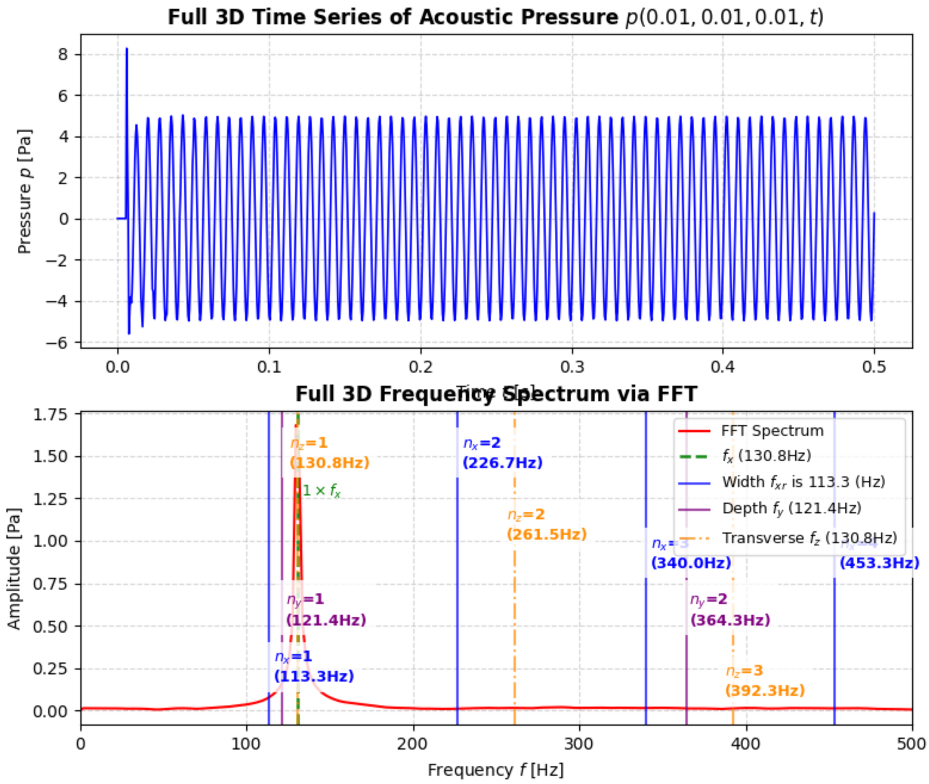

Fig. 7 Numerical Calculation Result (U = 1890.8(m/s))

5. Conclusion

Research on automobile whistling and suction sounds has been conducted in the past. For cavity resonance, a type of whistling sound, the cavity resonance frequency has been determined using Rossiter's empirical equation. Therefore, we limited our study to the three-dimensional case and clarified the physical phenomena that arise by solving a set of partial differential equations that explain the phenomenon. As a result, we were able to determine the frequency at which resonance increases, taking into account three-dimensional space. Finally, we were able to confirm the conditions under which resonance increases through numerical calculations.

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