

Derivation of Rossiter Formula in 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, limiting the study to the one-dimensional case, Rossiter formula was derived by solving a system of three differential equations. In addition, equations for the stability conditions of cavity resonance and the sound pressure were derived. Finally, the results were verified through numerical calculations, and reasonable conclusions were obtained.

Nomenclature

L_H : Maximum hole length

ρ, c : Air density and air sound speed

ω : Angular frequency

f, f_c : Frequency and cavity resonance frequency

k : Wavenumber

t : Time

j : Imaginary unit

U, U_{vortex} : 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 determined by edge shape
(dimension: L)

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

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

$H(x)$: Heaviside step function

s : Complex number

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, limiting ourselves to the one-dimensional case, we will represent cavity resonance as a physical phenomenon using three differential equations. Rossiter formula will be derived from these three simultaneous differential equations. Furthermore, the equations for the stabilization conditions of cavity resonance and the sound pressure equation will also be derived. Finally, we will verify it with numerical calculations.

These will be discussed below.

2. One-Dimensional Cavity Resonance

2.1. Vorticity Movement Equation

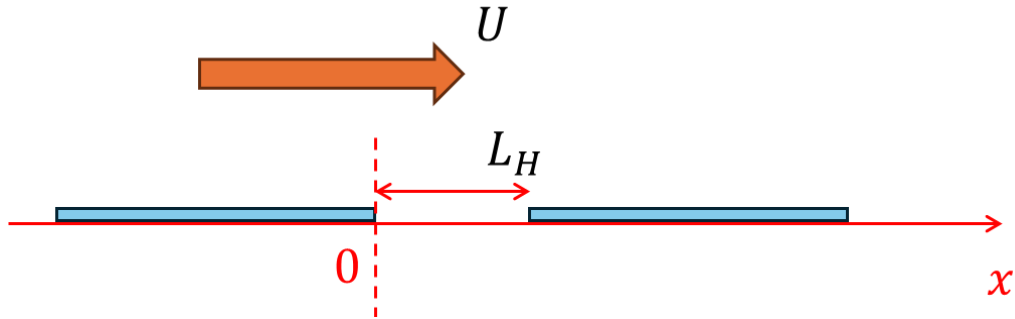


Fig. 1 1-Dimensional Board with Hole

Fig. 1 shows a board 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 one dimension. First, the movement equation of vorticity $\zeta(x, t)$ is expressed by the following equation. However, the viscosity term is ignored.

$$\frac{\partial \zeta}{\partial t} + U_{vortex} \frac{\partial \zeta}{\partial x} = 0 \quad (1)$$

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 one dimension, Powell's equation is given by the following:

$$\frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} - \frac{\partial^2 p}{\partial x^2} = \alpha \rho U \zeta(L_H, t) \delta'(x - L_H) \quad (2)$$

2.3. Boundary Conditions

Finally, we find the boundary conditions under which the velocity of the returning particles changes to vorticity. This is given by the following equation.

$$\zeta(0, t) = -\beta \frac{\partial}{\partial x} p(0, t) \quad (3)$$

3. Derivation of Rossiter Formula

3.1. Solution to the Vorticity Transfer Equation

Rossiter formula is derived by solving the three simultaneous differential equations, equations (1), (2), and (3). First, we solve equation (1). The solution when the boundary condition is $\zeta(0, t)$ is given by the following equation:

$$\zeta(x, t) = \zeta\left(0, t - \frac{x}{U_{vortex}}\right) \quad (4)$$

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 Green's functions in

the following form First, the Green's function is given by the following formula.

$$G(|x|, t) = -\frac{c}{2}H(ct - |x|) \quad (5)$$

From equation (2), the following equation is obtained.

$$\begin{aligned} p(x, t) &= \int_{-\infty}^t \int_{-\infty}^{\infty} G(x, t, \xi, \tau) \alpha \rho U \zeta(\xi, \tau) \delta'(\xi - L_H) d\xi d\tau \\ &= \int_{-\infty}^t \int_{-\infty}^{\infty} -\frac{\alpha \rho U c}{2} \zeta(\xi, \tau) H(c(t - \tau) - |x - \xi|) \delta'(x - L_H) d\xi d\tau \end{aligned} \quad (6)$$

Here, $\int f(\xi) \delta'(x - L) d\xi = -f'(L)$ is used.

$$p(x, t) = \int_{-\infty}^t \int_{-\infty}^{\infty} -\frac{\alpha \rho U c}{2} \left[-\frac{\partial}{\partial \xi} \zeta(\xi, \tau) H(c(t - \tau) - |x - \xi|) \right]_{\xi=L_H} d\xi d\tau \quad (7)$$

Continue the calculation. However, $\frac{\partial}{\partial \xi} \zeta(\xi, \tau)$ is mathematically smaller than $\frac{\partial}{\partial \xi} H(c(t - \tau) - |x - \xi|)$, and physically, the gradual change in vorticity during transport (derivative of ζ) has a small contribution, so it is ignored.

$$p(x, t) = \frac{\alpha \rho U c}{2} \int_{-\infty}^t \left[\zeta(L_H, \tau) \frac{\partial}{\partial \xi} H(c(t - \tau) - |x - \xi|) \right]_{\xi=L_H} d\tau \quad (8)$$

Integrate this equation, assuming $x \leq \xi$ and $x \leq L_H$. Also, the derivative of Heaviside step function is the delta function. We also applied the scaling property of the Dirac delta function.

$$\begin{aligned} p(x, t) &= \frac{\alpha \rho U c}{2} \int_{-\infty}^t \left[\zeta(\xi, \tau) \frac{\partial}{\partial \xi} H(c(t - \tau) - |x - \xi|) \right]_{\xi=L_H} d\tau \\ &= \frac{\alpha \rho U c}{2} \int_{-\infty}^t \left[\zeta(\xi, \tau) \delta(c(t - \tau) - |x - \xi|) \frac{\partial}{\partial \xi} (-|x - \xi|) \right]_{\xi=L_H} d\tau \\ &= \frac{\alpha \rho U c}{2} \int_{-\infty}^t [\zeta(\xi, \tau) \delta(c(t - \tau) - |x - \xi|) \cdot (-1)]_{\xi=L_H} d\tau \\ &= -\frac{\alpha \rho U c}{2} \int_{-\infty}^t \zeta(L_H, \tau) \delta(c(t - \tau) - |x - L_H|) d\tau \\ &= -\frac{\alpha \rho U c}{2} \zeta\left(L_H, t - \frac{L_H - x}{c}\right) \cdot \frac{1}{c} \\ \therefore p(x, t) &= -\frac{\alpha \rho U}{2} \zeta\left(L_H, t - \frac{L_H - x}{c}\right) \end{aligned} \quad (9)$$

Therefore, the following equation is obtained. This equation is the equation for the sound pressure generated by cavity resonance. Also, equation (4) was considered. However, $0 \leq x \leq L_H$.

$$p(x, t) = -\frac{\alpha\rho U}{2}\zeta\left(L_H, t - \frac{L_H - x}{c}\right) = -\frac{\alpha\rho U}{2}\zeta\left(0, t - \frac{L_H}{U_{vortex}} - \frac{L_H - x}{c}\right) \quad (10)$$

3.3. Vorticity Equation Considering Boundary Conditions

Finally, consider equation (3). Substitute equation (10).

$$\begin{aligned} \zeta(0, t) &= -\beta \frac{\partial}{\partial x} \left[-\frac{\alpha\rho U}{2} \zeta\left(L_H, t - \frac{L_H - x}{c}\right) \right]_{x=0} \\ &= \frac{\alpha\beta\rho U}{2} \frac{\partial}{\partial x} \left[\zeta\left(L_H, t - \frac{L_H - x}{c}\right) \right]_{x=0} \\ &= \frac{\alpha\beta\rho U}{2} \frac{\partial}{\partial t} \left[\zeta\left(L_H, t - \frac{L_H - x}{c}\right) \cdot \frac{\partial}{\partial x} \left(t - \frac{L_H - x}{c} \right) \right]_{x=0} \\ &= \frac{\alpha\beta\rho U}{2} \frac{\partial}{\partial t} \left[\zeta\left(L_H, t - \frac{L_H - x}{c}\right) \cdot \frac{1}{c} \right]_{x=0} \\ &= \frac{\alpha\beta\rho U}{2c} \frac{\partial}{\partial t} \zeta\left(L_H, t - \frac{L_H - 0}{c}\right) \end{aligned}$$

Therefore, the following equation is obtained. Here, equation (4) was considered.

$$\therefore \zeta(0, t) = \frac{\alpha\beta\rho U}{2c} \frac{\partial}{\partial t} \zeta\left(L_H, t - \frac{L_H}{c}\right) = \frac{\alpha\beta\rho U}{2c} \frac{\partial}{\partial t} \zeta\left(0, t - \frac{L_H}{U_{vortex}} - \frac{L_H}{c}\right) \quad (11)$$

3.4. Derivation of the Characteristic Equation

In equation (11), substituting $\zeta(0, t) = \zeta_0 e^{st}$ into both sides, we obtain the following equation:

$$\begin{aligned} \zeta_0 e^{st} &= \frac{\alpha\beta\rho U}{2c} \frac{\partial}{\partial t} \zeta_0 e^{s\left(t - \frac{L_H}{U_{vortex}} - \frac{L_H}{c}\right)} \\ &= \frac{\alpha\beta\rho U}{2c} s \zeta_0 e^{st} e^{s\left(-\frac{L_H}{U_{vortex}} - \frac{L_H}{c}\right)} \\ \therefore \zeta_0 e^{st} &= \frac{\alpha\beta\rho U}{2c} s \zeta_0 e^{st} e^{s\left(-\frac{L_H}{U_{vortex}} - \frac{L_H}{c}\right)} \end{aligned} \quad (12)$$

Eliminating $\zeta_0 e^{st}$ from both sides, we obtain the following equation.

$$1 = \frac{\alpha\beta\rho U}{2c} s e^{s\left(-\frac{L_H}{U_{vortex}} - \frac{L_H}{c}\right)} \quad (13)$$

Equation (13) is the characteristic equation.

3.5. Derivation of Rossiter Formula and Cavity Resonance Stabilization Conditions from the Characteristic Equation

By solving the characteristic equation, we derive Rossiter formula and the cavity

resonance stabilization conditions.

In the characteristic equation, we consider the properties by setting $s = \sigma + j\omega$. Here, since we want to determine whether "sound is produced or not," we consider the case when $\sigma = 0$. That is, $s = j\omega$. In this case, equation (13) becomes the following equation:

$$1 = \frac{\alpha\beta\rho U}{2c} \omega \cdot j \cdot e^{j\omega\left(-\frac{L_H}{U_{vortex}} - \frac{L_H}{c}\right)} \quad (14)$$

In equation (14), we consider the case when the phases of both sides are equal. In this case, sound is produced. Therefore, the following equation must hold.

$$\arg\left(\frac{\alpha\beta\rho U}{2c} \omega\right) + \arg(j) + \arg\left(e^{j\omega\left(-\frac{L_H}{U_{vortex}} - \frac{L_H}{c}\right)}\right) = -2\pi n \quad (15)$$

In equation (15), $\arg\left(\frac{\alpha\beta\rho U}{2c} \omega\right)$ is a positive value, so it is 0. $\arg(j)$ is $-\frac{\pi}{2}$.

$\arg\left(e^{j\omega\left(-\frac{L_H}{U_{vortex}} - \frac{L_H}{c}\right)}\right)$ is $\omega\left(-\frac{L_H}{U_{vortex}} - \frac{L_H}{c}\right)$. That is, the following equation is obtained.

$$\begin{aligned} 0 - \frac{\pi}{2} + \omega\left(-\frac{L_H}{U_{vortex}} - \frac{L_H}{c}\right) &= -2\pi n \\ \omega\left(-\frac{L_H}{U_{vortex}} - \frac{L_H}{c}\right) &= -2\pi n + \frac{\pi}{2} \\ 2\pi f_c\left(\frac{L_H}{U_{vortex}} + \frac{L_H}{c}\right) &= 2\pi n - \frac{\pi}{2} \\ f_c &= \frac{n - \frac{1}{4}}{\frac{L_H}{U_{vortex}} + \frac{L_H}{c}} \end{aligned} \quad (16)$$

Here, we use the following relationship:

$$U_{vortex} = \kappa U \quad (17)$$

$$M = \frac{U}{c} \quad (18)$$

Therefore, equation (16) becomes as follows:

$$f_c = \frac{U}{L_H} \frac{n - \frac{1}{4}}{\left(\frac{1}{\kappa} + M\right)} \quad (19)$$

This is exactly equivalent to Rossiter formula, which is the following equation. Empirically, we have used ϕ as 0.25, but we were able to derive $0.25 = \frac{1}{4}$ from the equation that describes the actual phenomenon.

$$f_c = \frac{U}{L_H} \frac{n - \phi}{\left(\frac{1}{k} + M\right)} \quad (20)$$

Now, when f_c is obtained from equation (16) or equation (19), that is, when $\omega = 2\pi f_c$, the gain G on the right side of the characteristic equation (14), which is equation (21), determines whether the self-excited oscillation of the cavity resonance is stable or unstable. That is, if $G > 1$, it is unstable, self-excited oscillation occurs, and the cavity resonance sound gets louder and louder. If $G < 1$, it is stable, and the sound decays until the cavity resonance sound stops. If $G = 1$, it is a critical state, and the cavity resonance sound is emitted at a constant volume.

$$G = \frac{\alpha\beta\rho U}{2c} \omega \quad (21)$$

3.6. Sound Pressure at a Position Outside the Sound Source ($x \geq L_H$)

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

$$p(x, t) = \frac{\alpha\rho U}{2} \zeta\left(L_H, t - \frac{x - L_H}{c}\right) = \frac{\alpha\rho U}{2} \zeta\left(0, t - \frac{L_H}{U_{vortex}} - \frac{x - L_H}{c}\right) \quad (22)$$

3.7. Derivation of α and β

Equations (2) and (3) are restated below.

$$\frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} - \frac{\partial^2 p}{\partial x^2} = \alpha\rho U \zeta(L_H, t) \delta'(x - L_H) \quad (23)$$

$$\zeta(0, t) = -\beta \frac{\partial}{\partial x} p(0, t) \quad (24)$$

Consider the quasi-static state in Equation (23); that is, neglect the time-dependent terms. This yields the following equation:

$$-\frac{d^2 p}{dx^2} = \alpha\rho U \zeta(L_H) \delta'(x - L_H) \quad (25)$$

Solving this equation using the Green's function yields the following expression

$$p(x) = -\frac{\alpha\rho U \zeta(L_H)}{2} \text{sgn}(x - L_H) + Ax + B \quad (26)$$

Here, the pressure gradient A inside the cavity is closely coupled with the fluid motion at the downstream edge. Considering the steady-state momentum conservation law (the linearized form of the Euler equations) and the spatial balance of the vortex force $\rho U \zeta$ in Howe's acoustic analogy, it is reasonable to assume that the internal pressure gradient is determined by the vorticity characteristics at the downstream end.

Therefore, based on physical consistency, the constant A is given by $A = -\rho U \zeta(L_H)$. This results in the following expression:

$$p(x) = -\frac{\alpha \rho U \zeta(L_H)}{2} \text{sgn}(x - L_H) - \rho U \zeta(L_H) x + B \quad (27)$$

Differentiating both sides with respect to x yields the following expression:

$$\frac{dp}{dx} = -\alpha \rho U \zeta(L_H) \delta(x - L_H) - \rho U \zeta(L_H) \quad (28)$$

Within the cavity ($0 \leq x \leq L_H$), the following expression is obtained:

$$-\frac{dp}{dx} = \rho U \zeta(L_H) \quad (29)$$

Considering the point $x = L_H$, the following equation is obtained:

$$\zeta(L_H) = -\frac{1}{\rho U} \frac{d}{dx} p(L_H) \quad (30)$$

From Equation (24), the following equation is also obtained at $x = 0$:

$$\zeta(0) = -\frac{1}{\rho U} \frac{d}{dx} p(0) \quad (31)$$

Thus, accounting for the time-dependent terms, the following equation is obtained:

$$\zeta(0, t) = -\frac{1}{\rho U} \frac{\partial}{\partial x} p(0, t) \quad (32)$$

Therefore, the following equation is obtained:

$$\beta = \frac{1}{\rho U} \quad (33)$$

Next, consider α . Based on Equation (25) and Howe's vortex sound theory, the following equation holds. Here, $\mathcal{G}_{space}$ is a positive geometric coefficient derived from the sharpness of the edge; the phase lag occurring during the conversion from vortex to sound is assumed to be zero.

$$\alpha = \mathcal{G}_{space} \cdot M \quad (34)$$

In the case of one-dimensional cavity resonance, where the cavity is formed by infinitely thin flat plates, $\mathcal{G}_{space}$ takes the following value:

$$\mathcal{G}_{space} = 1 \quad (35)$$

Therefore, the following equation is obtained:

$$\alpha = M \quad (36)$$

Now, substituting Equation (33) into Equation (21) and Equation (36) yields the following equation:

$$G = \frac{M \omega}{2c} \quad (37)$$

In other words, one can ascertain whether the cavity resonance is stable or unstable based on known values.

Based on the preceding discussion, the solution for vorticity, Equation (11) within the range $0 \leq x \leq L_H$ are given by the following equations:

$$\zeta(0, t) = \frac{M}{2c} \frac{\partial}{\partial t} \zeta \left(L_H, t - \frac{L_H}{c} \right) = \frac{M}{2c} \frac{\partial}{\partial t} \zeta \left(0, t - \frac{L_H}{U_{vortex}} - \frac{L_H}{c} \right) \quad (38)$$

4. Numerical Example

Based on previous results, a numerical example is shown below.

The physical quantities used in the calculation are shown in Table 1.

Table 1 Parameter Name and Value for Numerical Simulation

Parameter Name	Value
L_H	0.5(m)
κ	0.6(m/s)
U	34.0(m/s)
c	340.0(m/s)
ρ	1.2(kg/m ³)

Fig. 2 shows a graph plotting L_H on the horizontal axis and G on the vertical axis, based on Equation (37) with ω calculated by setting $n = 1$ in Equation (19) and with $\alpha = 1$. The graph reveals that the system is unstable when $L_H < 0.01334$ (m) and stable when $L_H > 0.01334$ (m). This value of L_H is determined by the following equation:

$$L_H = M \frac{\pi(1 - 0.25)}{\left(\frac{c}{\kappa U} + 1 \right)} \quad (39)$$

In other words, the maximum hole length L_H serves as the threshold between stability and instability. However, it does not take into account the fact that the phase lag associated with the conversion of vorticity into sound at the downstream end of the cavity (relative to the mainstream air velocity direction) does not ideally become zero. Consequently, this implies that the lower limit for the onset of cavity resonance under idealized conditions is $L_H = 0.01334$ (m).

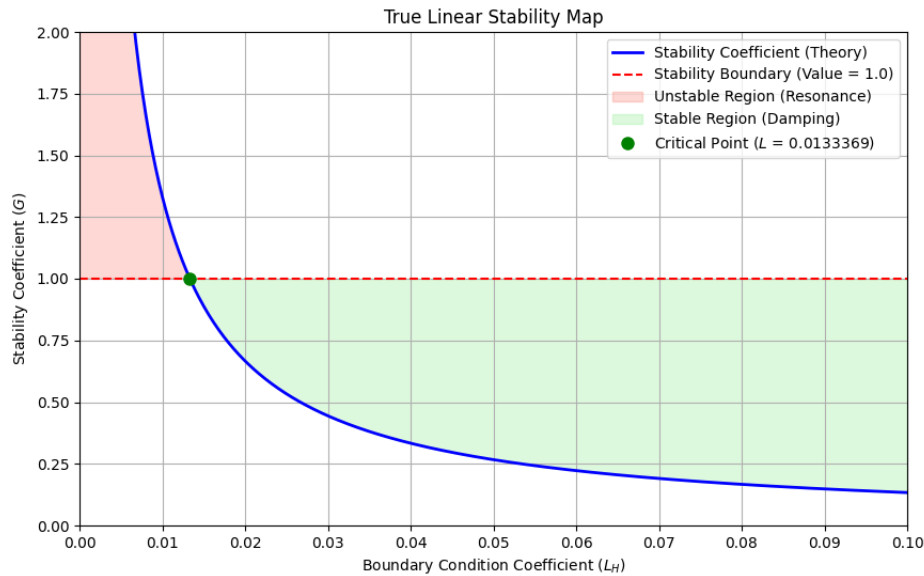


Fig. 2 Numerical Calculation Result (Stability Check)

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, limiting the study to the one-dimensional case, Rossiter's equation was derived by solving a system of three differential equations. In addition, equations for the stability conditions of cavity resonance and the sound pressure were derived. Finally, the results were verified through numerical calculations, and reasonable conclusions were obtained.

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