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Study of Quality and Damping Factor at First and Second Resonance of Closed Organ Pipe

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Abstract
The quality factor is a dimensionless physical quantity related to the damping factor present in the medium. The sound is recorded from the resonance tube experiment at the first and second resonating lengths. It is analyzed by PRAAT software to calculate the quality and damping factor. The quality factor varies from 12.50 to 146.70 and 6.32 to 130.95 at first and second resonant length respectively. In case of damping factor, it varies from 3.50x10^{-3} to 40.00x10^{-3} and 3.82 x10^{-3} to 79.11x10^{-3} at respective first and second resonating length. The ratio of the quality factor of the second resonance to that first resonance varies from 0.49 to 0.97 and for the damping factor that ratio varies from 1.02 to 2.02. The quality factor is higher at the first resonating length than at the second resonating length. The damping factor is lower in the first resonating length than in the second resonating length. From the experiment on the closed organ pipe, it was found that the system is under-damped due to the damping factor of less than one. At the first and second resonating lengths the relation between quality and damping factor is inversely nature.

Keywords: *frequency, resonating length, bandwidth, quality factor, damping factor.*

1. Introduction
When the air is blasting at the open end of the pipe, then a stationary wave is formed due to the superposition of the traveling wave through the open end and the reflected wave from the closed end of the pipe. Harmonics and overtones are produced on closed pipe, which is also known as resonance. Resonance is the phenomenon in which the amplitude becomes maximum as the external frequency coincides with the natural frequency (De Bedout et al., 1997). The general equation for different harmonics and overtones in the closed pipe is (Kinsler et al., 1999).

$$f_n = (2n+1)\frac{v}{4l} \quad \text{... (1)}$$

Where n = 0, 1 describe the first and second resonance, *v* and *l* be the velocity of sound and length of closed pipe.

The sound produced by pipe can be analyzed by the stationary spectrum and which helps to characterize the sound properties (Angster et al., 2000).

The quality factor is a dimensionless physical quantity that explains the behavior of an oscillator is underdamped, overdamped, or critically damped. The quality factor measures the ratio of energy stored to the energy dissipated per cycle (Hick man and Ian, 2013; Tooley and Michael, 2006). To measure the quality factor, resonant frequency (f_r) and two other frequencies f_1 and f_2 on either side are required, where the values of f_1 and f_2 are 0.707 of f_r. The difference between f_1 and f_2 (f_2-f_1) is called bandwidth. The quality factor is highly affected the by oscillating frequency of the organ pipe (Auvray et al., 2006). The quality factor describes the behavior of a simple damped oscillator as overdamped, underdamped, and critically damped when Q < 0.5, Q > 0.5 and Q = 0.5 respectively (James, 1989; Sabah and Nassir, 2017).

Damping is an influence on the oscillation system which reduces its oscillation. Damping is produced by processes that dissipate the energy stored in the oscillation (Steidel, 1971). If the value damping factor is less than one, then the system is underdamped. If greater than one, then the system is overdamped. If equal to one, then the system is critically damped. From the experiment of different sets of cylindrical pipes having different diameters at the same frequencies, it was found that quality factor and energy losses near the pipe due to sound radiation (Moloney and Hatten, 2001). With the help of the second-order transfer function, amplitude-frequency resonance due to swept oscillations is estimated. Which can help to estimate the damping coefficient (Placzynski, 2016).

After the study of quality factor, damping coefficient, energy loss by different cylindrical open pipe, this paper attempts to explain about the sound production by a closed organ pipe having different qualities at first and second resonance. Which helps to determine the damping factor at this condition of the pipe.

2. Theory

The energy dissipation of the oscillator is represented by the quality factor which is mathematically defined as (Chow, 1995)

$$Q = 2\pi \frac{\text{stored energy in oscillation}}{dissipated\ energy} \quad \text{... (2)}$$

The high-quality factor gives the information of low energy dissipation whereas the low-quality factor means large damping of amplitude and energy.

The time-dependent signal of the resonance is

$$S(t) = e^{-r(\beta - i\omega_r)}\, u(t) \quad \text{... (3)}$$

where β is the decay constant and ω_r is the resonant angular frequency. The Fourier transform of S(t) is

$$|S(\omega)|^2 = \frac{1}{\beta^2 + (\omega - \omega_r)^2} \quad \text{... (4)}$$

When $\omega = \omega_r$ then maximum value of $|S(\omega)|^2 = \frac{1}{\beta^2}$ ... (5)

When $\omega = \omega_1 - \beta$ and $\omega = \omega_2 = \omega_r + \beta$ ... (6)

Then half max frequencies occur. So that band width or resonance width can be defined as $2\beta = \omega_2 - \omega_1$

Finally quality factor can be defined as

$$Q = \frac{\omega_r}{2\beta}$$

$$Q = \frac{\omega_r}{\omega_2 - \omega_1}$$

$$Q = \frac{f_r}{f_2 - f_1}$$ where $\omega_1 = 2\pi f_1$, $\omega_2 = 2\pi f_2$ and $\omega_r = 2\pi f_r$

$$Q = \frac{f_r}{\text{Band width}} \quad \text{... (7)}$$

Where $f_2 - f_1 = BW$ is called band width, f_r is resonant frequency, and f_1 and f_2 are lower cut of frequencies or frequencies below 3dB of resonant frequency.
The damping factor ϒ is related to quality factor by the relation

$$\gamma = \frac{1}{2Q} \quad \text{... (8)}$$

To attempt the main objective of the paper, at first, by measuring the value of bandwidth (BW) we calculate the quality factor (Q) by using equation (7). Then calculate the damping factor by using the quality factor (Q) from equation (7). Where wall loss and sound radiation loss-like parameters on the closed pipe are not considerable.

3. Method

A vibrating tuning fork is held slightly above the free end of the tube, then the water level is adjusted till an approximate resonance is obtained. The sound is recorded at the first and second resonance. This recorded sound is analyzed with Praat software to calculate the quality factor and damping factor.

Fig.1. Recording the sound at first and second resonance by resonance tube apparatus.

4. Results and discussions

Table-1: Measurement of resonating length, bandwidth, quality factor, and damping factor at first and second resonance in a closed organ pipe for tuning fork having different frequencies.

S. N.	Resonance Frequency (Hz)	At first resonance				At second resonance			
		Resonating Length (L_1 cm)	Band width BW_1 (Hz)	Quality factor Q_1	Damping factor ($\times 10^{-3}$)	Resonating Length (L_{2cm})	Band width BW_2 (Hz)	Quality factor Q_2	Damping factor ($\times 10^{-3}$)
1	512	16.0	4.49	146.70	3.50	50.0	3.91	130.95	3.82
2.	480	17.5	3.90	123.08	4.10	54.0	4.01	119.70	4.18
3	426	19.5	3.62	117.68	4.25	61.0	4.62	92.21	5.42
4	405	21.0	3.71	109.10	4.58	65.0	5.83	69.47	7.20
5	384	22.0	4.52	84.96	5.89	69.0	6.24	61.54	8.13
6	362	22.5	7.67	47.20	10.59	71.0	8.37	43.23	11.57
7	341	25.0	11.16	30.56	16.36	76.5	21.37	15.96	31.33
8	320	26.5	18.18	17.60	28.41	82.0	32.87	9.74	51.34
9	288	30.0	18.40	15.65	31.95	91.2	37.21	7.74	64.60
10	256	33.0	20.48	12.50	40.00	98.0	40.48	6.32	79.11

Table-2: Measurement of the ratio of quality factor and damping factor at second resonance to first resonance in a closed organ pipe.

S. N.	At first resonance			At second resonance			Ratio $\frac{Q_2}{Q_1}$	Ratio $\frac{\gamma_2}{\gamma_1}$
	Resonating Length (L_{1cm})	Quality factor Q_1	Damping factor (Υ_1) ($\times 10^{-3}$)	Resonating Length (L_{2cm})	Quality factor Q_2	Damping factor (Υ_2) ($\times 10^{-3}$)		
1	16.0	146.70	3.50	50.0	130.95	3.82	0.89	1.10
2.	17.5	123.08	4.10	54.0	119.70	4.18	0.97	1.02
3	19.5	117.68	4.25	61.0	92.21	5.42	0.78	1.28
4	21.0	109.10	4.58	65.0	69.47	7.20	0.64	1.57
5	22.0	84.96	5.89	69.0	61.54	8.13	0.73	1.38
6	22.5	47.20	10.59	71.0	43.23	11.57	0.92	1.10
7	25.0	30.56	16.36	76.5	15.96	31.33	0.52	1.92
8	26.5	17.60	28.41	82.0	9.74	51.34	0.53	1.81
9	30.0	15.65	31.95	91.2	7.74	64.60	0.49	2.02
10	33.0	12.50	40.00	98.0	6.32	79.11	0.51	1.98

Table-3: Coefficient of correlation of first resonating length with quality factor and damping factor.

S.N	Resonating Length (L_1cm)	Quality factor Q_1	Damping factor (Υ_1) ($\times 10^{-3}$)	Correlation between L_1 and Q_1	Correlation between L_1 and Υ_1	Correlation between Q_1 and Υ_1
1	16.0	146.70	3.50	-0.92	0.95	-0.88
2.	17.5	123.08	4.10			
3	19.5	117.68	4.25			
4	21.0	109.10	4.58			
5	22.0	84.96	5.89			
6	22.5	47.20	10.59			
7	25.0	30.56	16.36			
8	26.5	17.60	28.41			
9	30.0	15.65	31.95			
10	33.0	12.50	40.00			

Table-4: Coefficient of correlation of second resonating length with quality factor and damping factor.

S.N	Resonating Length (L_2cm)	Quality factor Q_2	Damping factor (Υ_2) ($\times 10^{-3}$)	Correlation between L_2 and Q_2	Correlation between L_2 and Υ_2	Correlation between Q_2 and Υ_2
1	50.0	130.95	3.82	-0.92	0.95	-0.82
2.	54.0	119.70	4.18			
3	61.0	92.21	5.42			
4	65.0	69.47	7.20			
5	69.0	61.54	8.13			
6	71.0	43.23	11.57			
7	76.5	15.96	31.33			
8	82.0	9.74	51.34			
9	91.2	7.74	64.60			
10	98.0	6.32	79.11			

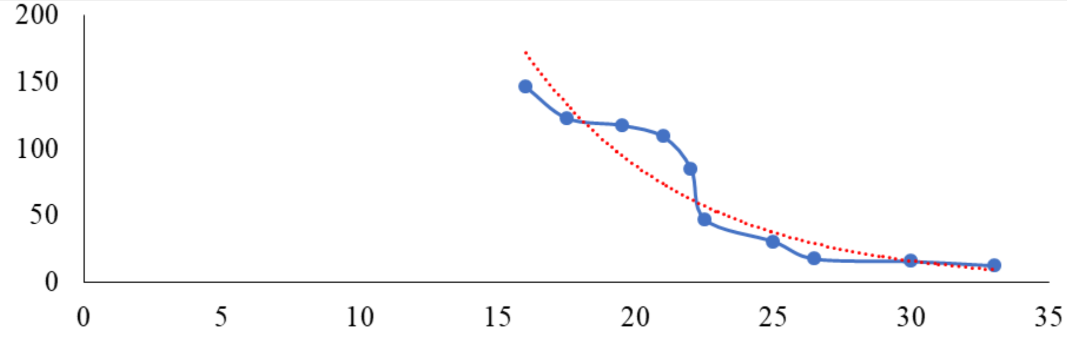

Fig.2. The solid line is graph between quality factor and resonating length at first resonance. The red dot line represents the trend line equation.

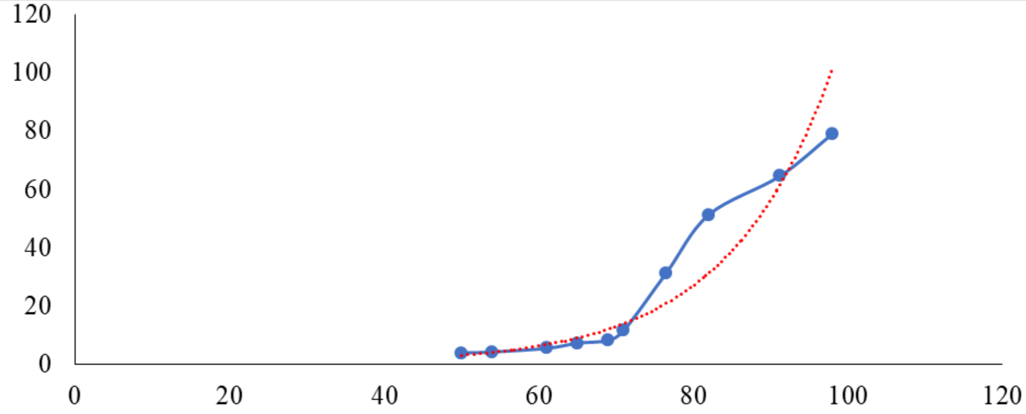

Fig.3. The solid line is graph between damping factor and resonating length at first resonance. The red dot line represents the trend line equation.

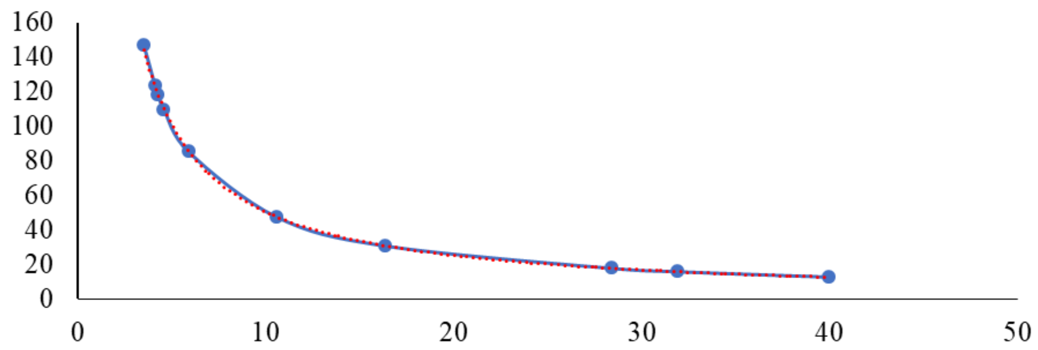

Fig.4. The solid line is graph between damping and quality factor at resonating length. The red dot line represents the trend line equation.

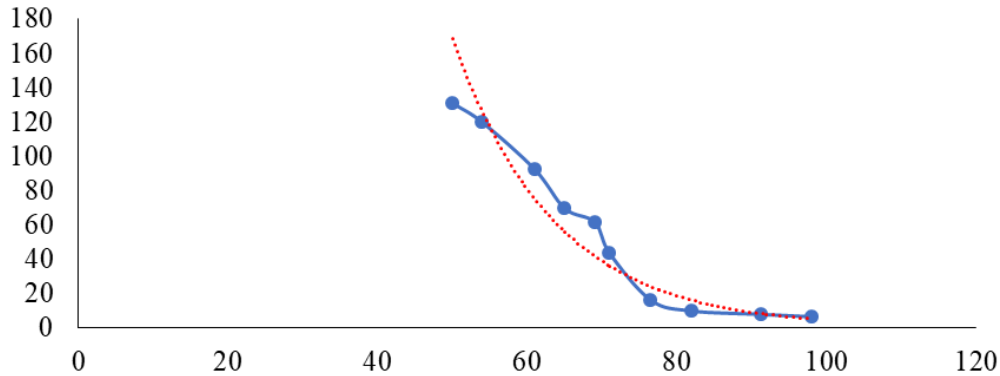

Fig.5. The solid line is graph between quality factor and resonating length at second resonance. The red dot line represents the trend line equation.

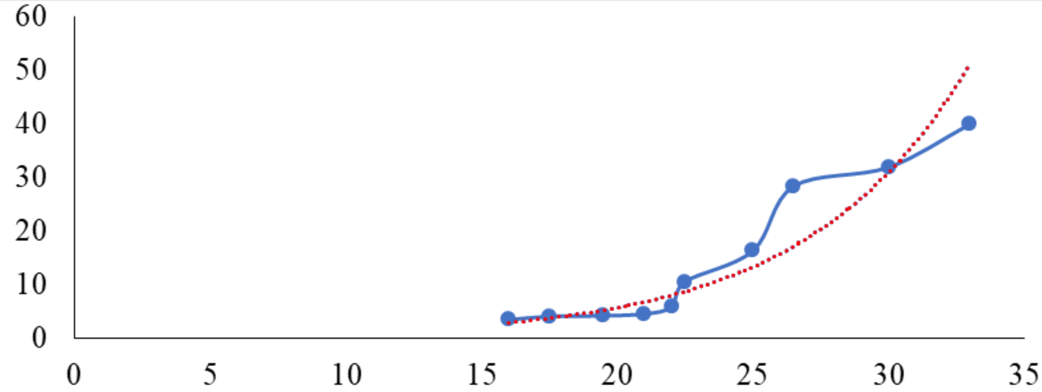

Fig.6. The solid line is graph between damping factor and resonating length at second resonance. The red dot line represents the trend line equation.

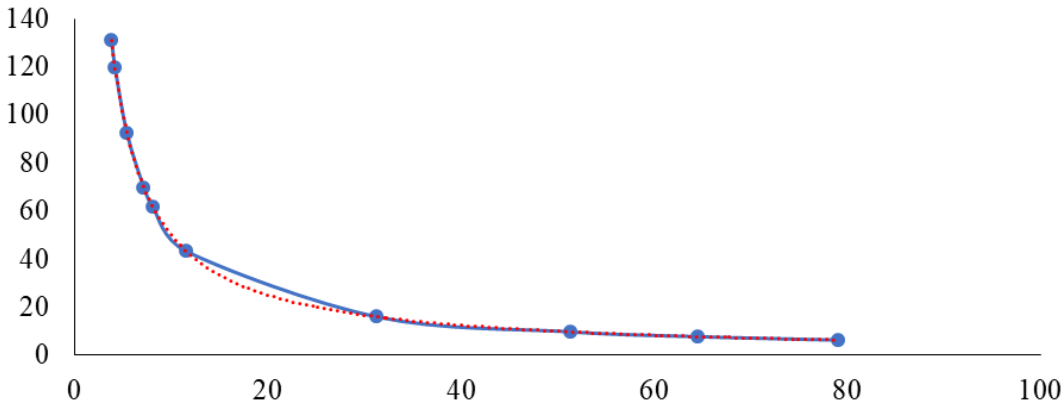

Fig.7. The solid line is graph between damping and quality factor at second resonating length. The red dot line represents the trend line equation.

Table 1 shows the variation of the quality factor and damping factor at the first and second resonating lengths.

4.1 Quality factor

The maximum value of quality factors (Q value) is 146.70 and 130.95 at first and second resonating lengths of 16.0 cm and 50.0 cm respectively. 12.50 and 6.32 are minimum Q values at respective resonating lengths of 33.0 cm and 98.0 cm. The variation of a quality factor with first and second resonating lengths is shown in Figures 2 and 5.

From figures 2 and 5, the trend line equation for quality factor and resonating length at first and second resonance is $Q_1 = 2577.9\, e^{-0.169L_1}(R^2 = 0.87)$ and $Q_2 = 6675.7\, e^{-0.074L_2}(R^2 = 0.91)$ have approximately nearly the same negative exponential nature.

4.2 Damping factor

The maximum value of damping factors is $40.00\text{x}10^{-3}$ and $79.11\text{x}10^{-3}$ at first and second resonating lengths 33.0 cm and 98.0 cm whereas minimum values are $3.50\text{x}10^{-3}$ and

3.82 x10^{-3} at respective first and second resonating length 16.0 cm and 50.0 cm. Fig 3 and 6 show the variation a damping factor with the first and second resonating lengths. From Fig. 3 and 6 the trend line equation for the damping factor (γ) and resonating length at first and second resonance are γ_1=0.199$e^{0.1683L_1}$ (R^2=0.87) and γ_2=0.075$e^{0.0736L_2}$ (R^2=0.87) have approximately nearly the same positive exponential nature.
In table 2 the ratio of a quality factor at the second resonating length to the first resonating length varies from 0.49 to 0.97 which indicates that the quality factor at the first resonating length is greater than the second resonating length.
In the case of the damping factor, this ratio varies from 1.02 to 2.02, which means the damping factor present in the second resonating length is greater than at first resonating length.
Tables 3 and 4 found that the coefficient of correlation of quality factor with the first and second resonating lengths are -0.92 and -0.94. That means quality factor and resonating length are significantly correlated with each other with the same negative exponentially nature as in Fig. 2 and 5. The coefficient of correlation of the damping factor with the first and second resonating length (air column length) are 0.95 and 0.94 respectively. So, they are significantly correlated with each other with the same positive exponential nature as in Fig. 3 and 6.
Tables 3 and 4 found that the coefficient of correlation between the quality factor and damping factor at the first resonance is -0.88 and at the second resonance is -0.82. That means the quality factor and damping factor are inversely related to each other at first and second resonance.
From Fig. 4 and 7 the trend line equation of quality factor and damping factor at first and second resonance are Q_1=507.00$\gamma_1^{-1.004}$ and Q_2=500.29γ_2^{-1} respectively that means quality factor and damping factors are inversely related to each other.

5. Conclusion

In comparison first and second resonating lengths, the quality factor is highest at the first resonating length due to the lowest damping factor present in the short air column length (resonating length). Quality factor decreases for the second resonating length due to the damping factor present in longer air column length.
From the above discussion, it was found that the high-quality factor is obtained at lowest resonating length (air column length) which has the lowest damping factor. The lowest quality factor is obtained at the longest resonating length which has the highest damping factor in case of both first and second resonance condition.
The quality factor and damping factor are inversely varying at first and second resonating lengths.
In a closed organ pipe damping factor is less than 1 so the system is underdamp.
This experiment support to further analysis of the quality of sound and damping factor at different resonance. Further it will be help to perception of sound at different type of cylindrical closed pipe.

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