AN EXPERIMENTAL STUDY OF THE HERSCHEL-QUINCLE (HQ) TUBE NOISE ATTENUATION PERFORMANCE

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Abstract

The work presented in this paper summarize both analytical and experimental investigations of the Herschel-Quincke (HQ) concept for reducing known radiated inlet noise using signal generating system. The analytical part of this work involves one-dimensional plane wave propagate in a cylindrical duct. In this paper adaptive HQ tube is used to reduce tonal noise propagating as plane waves in closed end duct. The effect of HQ tube length on the noise reduction, induced by a loudspeaker at various frequencies, is investigated experimentally in an acoustically cylindrical duct with and without HQ. Five HQ tubes with different lengths are investigated. The distance between the HQ tube ends is kept constant ($l=20$ cm), ($L_{HQ}/l = 1.5, 2.5, 3, 3.5, \text{ and } 4$). Two Microphones system was used to measure the net acoustic power transmission in the duct. One microphone is located just before the HQ tube in the duct, and the other is at the closed end of the duct where it is always anti-node pressure. Data acquisition, monitoring and analysis are done using National Instrument DAQ card and LabVIEW software. A LabVIEW vi code is developed to interface and process the two microphones system signals. Results showed that the length of the HQ tube is very important for a passive control of the noise reduction. While long HQ tube was effective in noise reduction in low frequencies, short HQ tube was more effective for high frequencies.

Keywords: Herschel-Quincke, Acoustics, passive control, signal processing

Introduction

The concept of Herschel Quincke (HQ) tube as a noise reduction device; which is known since the beginning of the 20th century; has shown its potential to reduce the noise at some specific frequencies.

HQ-tube (Selamet, and et al., 1994) is, as shown in figure (1), a tube attaches to the main duct at two points along its axis. When an incident plane-wave travels in the duct to the right and encounters the first branch, named the inlet of HQ-tube, divides and will recombined later at the second intersection, named the outlet of HQ-tube. A phase shift between the recombined signals and consequently attenuation or reduction of sound will be created by changing HQ-tube parameters at a number of discrete frequencies.

Noise control strategies can be characterized as active, passive, or a combination of both passive and active approaches. A Herschel-Quincke (HQ) tube is one of the passive noise control techniques.

Studies of Herschel-Quincke (HQ) tube for varying lengths and cross sectional areas, has been carried out since the 19th century, first by Herschel and Quincke Herschel (1833) and Quincke (1866) and later refined by Stewart (1928), Stewart, and et al (1930) and Stewart, G. W. (1945) in the early 20th century.

The Herschel-Quincke (HQ) tube concept consists of installing circumferential arrays of HQ tubes around the inlet and/or the by-pass duct of a turbofan engine. The application of HQ tubes to turbofan engine inlet noise is a developing technique originally pioneered at (Virginia Tech Jerome, and et al., 2002).

Taleb et al (2017) investigate the effect of the HQ (Herschel-Quincke) tube length on the reduction of noise. An acoustically cylindrical duct with and without HQ induced by a loudspeaker at various frequencies. Microphone system has been used to measure the net acoustic power transmission in the duct downstream with HQ tube and compared in the duct without the HQ tube. The cylindrical duct is an open-open end, with a wall thickness of 0.25 cm, and has a length and inner diameter of 107 cm and 20 cm respectively. There are two types of HQ tubes mounted on the side of the duct, in the first; is a short HQ tube with a length of 14 cm, and its diameter of 4 cm. Tube is fixed at 59 cm from the loudspeaker. The other; is the long HQ tube with length of 72 cm, and with a diameter of 4 cm, this type of HQ is fixed at 31 cm from the loudspeaker. In their study the distance between the inlet and the outlet of the HQ was changed. In this paper the HQ-tube length is changed to study its effect on the performance of the HQ-tube attached to a closed end duct.

Experimental setup

A diagram of the experimental setup is shown in figure 1. In this case of study cylindrical tube with a single HQ tube is used to decrease the noise as shown in figure (1). Basically, the test rig consists of a cylindrical tube with and without HQ tube, a signal generator system, and a microphone system. The cylindrical tube is a closed end, and the other end is closed by a vibrating diaphragm of a loudspeaker, the tube has a length and an inner diameter of 1.0 m and 0.12 m respectively. The HQ tubes with inner diameter of 35 mm, and with different length (L_{HQ}) have been used, the distance between the HQ tube ends (l) is 20 cm, in this paper; $L_{HQ}/l = 1.5, 2.5, 3, 3.5, \text{ and } 4$ are used. The closed tube is acoustically excited by a signal generating system, includes a signal generator (type Peak Tech.), an amplifier, and a loudspeaker. The amplitude of the supply voltage for the loudspeaker is kept constant during these experiments, the loudspeaker has a maximum power of 250 W and a frequency range of 20 to 4000 Hz. Its effective diaphragm radius is 0.06 m; sinusoidal signal mode has been selected to excite air in the tube. Almost every acoustic measurement arrangement contains microphones that normally

convert sound pressures into electrical signals; an electrostatic (capacitor) type of microphone is used in these experiments for the measurement of sound pressure. The microphone is mounted at the closed end of the tube as shown in the Figure 1, a pre-amplifier and an amplifier used to amplify the captured signal by microphone from few milli-volts to few volts. National Instrument DAQ card and LabVIEW software have been applied for data acquisition, monitoring and analyses.

Figure (1): Schematic diagram of test rig

Solution of Wave Equation for Air in a Close Top Tube and Closed by a Vibrating Diaphragm at the Bottom End

Considered here that the sound field in a rigid tube that is closed at one end by a vibrating diaphragm of a loudspeaker with rms velocity of u_o , the other end is closed. The boundary condition at $z = 0$, the fluid velocity at the diaphragm face is equal to the velocity of the diaphragm (u_o) (Temkin, S., 1981)

The total length of the tube is L , and λ is a wavelength, one solution which will satisfy the wave equation is given by the superposition of the complex pressure associated with a positive-going and negative going plane wave. Thus.

$$p(z,t) = Ae^{-j(kz-\omega t)} + Be^{j(kz+\omega t)} \quad 1$$

Where A and B are arbitrary complex number which represent the amplitude and relative phases of the wave travelling in the positive and negative direction respectively. The magnitudes of A

and B are determined from boundaries conditions. When the magnitude of the velocity along tube is zero, the magnitude of the pressure is at the maximum, and vice versa.

From Euler's equation for plane wave

$$u(z, t) = -\frac{1}{j\omega\rho_o} \frac{\partial p}{\partial z} \quad 2$$

the derivative of p in equation (1) with respect to z :

$$\frac{\partial p}{\partial z} = -jAke^{-j(kz-\omega t)} + jBke^{j(kz+\omega t)} \quad 3$$

and substitute into Euler's Equation (2):

$$u(z, t) = \frac{k}{\rho_o \omega} (Ae^{-j(kz-\omega t)} - Be^{j(kz+\omega t)}) \quad 4$$

Since $k = \frac{\omega}{c_o}$, where c is speed of sound in fluid, expression can be simplified:

$$u(z, t) = \frac{1}{\rho_o c_o} (Ae^{-j(kz-\omega t)} - Be^{j(kz+\omega t)}) \quad 5$$

the boundaries conditions are;

$$\left. \frac{\partial p}{\partial z} \right|_{z=L} = 0$$

$$u = 0 \text{ at } Z = L$$

$$u = u_o \text{ at } Z = 0$$

$$A - B = u_o c_o \rho_o$$

$$A = \frac{u_o c_o \rho_o e^{jkl}}{2j \sin kl} \quad \text{and} \quad B = \frac{u_o c_o \rho_o e^{-jkl}}{2j \sin kl}$$

$$u(z, t) = \frac{\omega l}{\sin kl} \cos \omega t \sin(k(L - z)) \quad 6$$

the corresponding acoustic pressure is;

$$p'(z, t) = c_o \rho_o \frac{\omega l}{\sin kl} \sin \omega t \cos(k(L - z)) \quad 7$$

Pressure Fluctuating $P'(z, t)$

$$P(z, t) = \bar{p} + p'$$

$$p(z, t) = p'$$

$$\overline{p'^2} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T p'^2 dt \quad [\text{ref}] \quad 8$$

$$p'(z, t) = c_o \rho_o \frac{\omega l}{\sin kl} \sin \omega t \cos(k(L - z))$$

$$p'^2(z, t) = \left(c_o \rho_o \frac{\omega l}{\sin kl} \sin \omega t \cos(k(L - z)) \right)^2$$

$$\overline{p'^2(z, t)} = \frac{1}{T} \int_0^T \left(c_o \rho_o \frac{\omega l}{\sin kl} \sin \omega t \cos(k(L - z)) \right)^2 dt$$

$$\overline{p'^2(z, t)} = \frac{1}{T} \int_0^T \left(c_o \rho_o \frac{\omega l}{\sin kl} \cos(k(L - z)) \right)^2 \sin^2 \omega t dt$$

$$\sin^2 \omega t = \frac{1}{2} (1 - \cos 2\omega t)$$

$$\overline{p'^2(z, t)} = \frac{1}{T} \int_0^T \left(c_o \rho_o \frac{\omega l}{\sin kl} \cos(k(L - z)) \right)^2 \sin^2 \omega t dt$$

$$\sin^2 \omega t = \frac{1}{2} (1 - \cos 2\omega t)$$

$$\overline{p'^2(z, t)} = \frac{1}{T} \left(c_o \rho_o \frac{\omega l}{\sin kl} \cos(k(L - z)) \right)^2 \left(\frac{1}{2} \left(t - \frac{\sin 2\omega t}{2\omega} \right) \right)_0^T$$

$$\overline{p^{2'}(z,t)} = \left(c_o \rho_o \frac{\omega l}{\sin kl} \cos(k(L-z)) \right)^2 \left(\left(\frac{1}{2} - \frac{\sin 2\omega T}{4\omega} \right) \right)$$

Root mean square of Pressure fluctuating Prms

$$P_{rms} = \sqrt{\overline{p^{2'}(z,t)}} = \left(c_o \rho_o \frac{\omega l}{\sin kl} \cos(k(L-z)) \right) \sqrt{\left(\left(\frac{1}{2} - \frac{\sin 2\omega T}{4\omega} \right) \right)}$$

$$P_{rms}(z=L) = \left(c_o \rho_o \frac{\omega l}{\sin kl} \right) \sqrt{\left(\left(\frac{1}{2} - \frac{\sin 2\omega T}{4\omega} \right) \right)}$$

Normalized acoustic pressure to the Prms at z= L

$$\frac{P_{rms}(z)}{P_{rms}(L)} = |\cos(k(L'-z))|$$

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$$k = \frac{2\pi}{\lambda}, \lambda = \frac{c_o}{f}, k = \frac{\omega}{c_o}, \text{ and } c_o = \sqrt{\gamma RT}$$

where:

k is the wave number

ω is the angular frequency [rad/s]

λ is the wave length [m]

c_o is the speed of the sound [m/sec]

f is the frequency [Hz]

R is the gas constant [$\frac{J}{kg.K}$]

γ is the specific heat ratio

T is the temperature [K]

For closed tube at the end

$$\lambda_n = \frac{4L}{(2n-1)} \quad n = 1, 2, 3, 4, 5, \dots$$

L is the tube length [m]

$$f_n = (2n-1)f_1 \quad 10$$

Figure (2) shows the variation of the normalised pressure $(p_{rms}(z)/p_{rms}(L))$ variations as a function of the tube length for first six modes, by using Eq. 9. At $z = 0$, the *rms* velocity is u_o and at $z = L$, $\partial P/\partial z = 0$, the period $T = 1/f$.

The fundamental mode of this tube is 85 Hz, high order modes using equation 10, (255 Hz, 425 Hz, 595 Hz,)

Figure (2): six theoretical acoustic pressure modes along the tube

Experimental Measurements of the Tube Harmonics

To evaluate the relative amplitude of *rms* acoustic pressure at different excitation frequencies, the *rms* pressure at the pressure anti-node is measured using a microphone system, which is located at the closed end of the tube, because this location always has maximum *rms* acoustic pressure amplitude for all harmonics, whereas the other pressure anti-node locations vary along the tube with the excitation frequencies. The excitation frequency applied was varied from 20 Hz, which is the lowest frequency response of the loudspeaker, to 2500 Hz. The voltage applied to the loudspeaker was maintained at 8 volts. By using the data acquisition system, the digital signal generator is connected to the loudspeaker through a digital to analogue (D/A) channel and the signals picked up by the microphone which is connected to the data acquisition system

through the analogue to digital (A/D) channel. Figure (3) presents the *rms* pressure in volts as a function of excitation frequency. It can be seen from the figure that the first pressure *rms* peak appears at 85 Hz which represents the fundamental mode of this rig. The second peak appears at 245 Hz, which represents the second mode and third mode at 408 Hz fourth mode at 570 Hzetc. It is also clearly seen that the ratio between all the peaks is 1: 2: 3: ..., and so on, which is in a good agreement with the theoretical analysis of the wave equation of acoustic pressure.

Figure (3): The *rms* acoustic pressure as a function of the excitation frequency (f_e).

Figure (4) illustrates the first six wave modes of the measured *rms* pressure along the tube. The *rms* pressure is measured using a microphone, which is moving along the tube whilst keeping the loudspeaker at a constant power. From the figure the maximum *rms* acoustic pressure amplitude for all harmonics at the closed end of the tube, whereas the other pressure anti-node locations vary with the excitation frequency. The trends of the modes are very close to the theoretical calculation of the closed end tube with an end-mounted loudspeaker. From the Figure, it can also be seen that the pressure fluctuations (*rms*) are periodic along the tube. For this reason, this will be analyzed further, in this paper, in terms of time series history and power spectrum.

Figure (4): First seven experimental acoustic pressure modes of the tube (n=2,3,4,5,6,7, and 8)

The HQ tubes with inner diameter of 35 mm, and with different length (L_{HQ}) have been used, the distance between the HQ tube ends is (l)=20 cm, in this paper; $L_{HQ}/l = 1.5, 2.5, 3, 3.5$, and 4 are used. Figure (5) shows the zoom-in of the second beak shown in figure 3. It can be seen that the HQ-tube length has a significant effect on the noise reduction where at low frequency of 206 Hz the longest HQ-tube (80 cm) was the most effective with reduction of 80.9%. While the shorter length of 60 cm, at the same frequency (206 Hz) was less effective.

As the frequency increases the reduction noise was most effective with shorter HQ-tube length e.g. at frequency of 263 Hz the maximum reduction (93.1%) with HQ-tube length of 60 cm. For all HQ-tube lengths tested in this work the reduction of noise in the second beak is summarized in table (1). From this table it can be seen that the shorter lengths of HQ-tube (20 and 30 cm), the pressure fluctuation (rms) are higher than that without HQ-tube with a percent of 4.63 and 19.11 respectively.

Table (1): reduction of the noise with and without HQ at the second peak

Second Peak (Second Harmonic)					
HQ length [cm]	without HQ	with HQ	Excitation Frequency	Reduction percentage	state
30	5.64	5.901	238	-4.62766	Increase
50	4.7768	5.69	227	-19.1174	Increase
60	4.7369	0.3228	263	93.18542	Decrease
70	5.65	0.392	237	93.06195	Decrease
80	3.54	0.6738	206	80.9661	Decrease

Figure (5): The zoom-in of the second beak in the Figure (3)

Figures (6), (8), and (10) show the time series with signal amplitude. These figures show that the received signal by microphone is a sine wave, the same as the applied signal at different HQ-tube length of 60, 70, and 80 cm and without HQ. The reduction in the noise by all HQ-tube lengths is seen very clearly in these figures. Results show that all the signals have a sinusoidal form, but with HQ the signal is less in amplitude due to the reduction effect.

Figures (7), (9), and (11) show the power spectrum of the signals for all HQ-tube lengths tested and without the HQ-tube. The signals are rigorously analyzed by using LabVIEW software. The analysis is done on the basis of time history and power spectrum. The sampling rate is 5000 samples per second and the duration of each sampling is 4 second. (Number of samples is 20,000).

Results of power spectrum show that, only one peak at the same applied frequency of signal generator, and also here less amplitude of power spectrum with HQ tube, that means the signals are very pure signal without any sub-harmonics and with reduction in noise by using the HQ technique.

Figure (6): Time history of the acoustic signals, without and with the longest HQ at frequency of 206 Hz. HQ-Tube length of 80 cm

Figure (7): the power spectrum of the signal at the applied frequency of 206 Hz without HQ, and with HQ-Tube length of 80 cm

Figure (8): Time history of the acoustic signals, without and with the middle HQ at frequency of 237 Hz, HQ-Tube length of 70cm

Figure (9): The power spectrum of the signal at the applied frequency of 237 Hz without HQ, and with HQ-Tube length of 70 cm

Figure (10): Time history of the acoustic signals, without and with the shortest HQ at frequency of 263 Hz. HQ-Tube length of 60cm

Figure (11): The power spectrum of the signal at the applied frequency of 263 Hz without HQ, and with HQ-Tube length of 60 cm

Conclusions

A passive noise HQ-tubes technique is used to reduce tonal noise propagating as plane waves in ducts. Optimal tuning analysis has been achieved by using a pressure sensor (Microphone system) located in the duct at the closed end. This work presented a tuned duct with and without

HQ-Tube technique that can be used to quiet noise in enclosed acoustic systems. It represents a powerful tool of noise controlling in tuning acoustic systems. In this paper; it has been concluded that the length of the HQ tube plays a significant role in noise reduction and control as presented in table 1, for low frequency the long tube should be used to attenuate the noise, and short HQ tube for high frequency. In addition, the collected data can be helpful in the development of modeling schemes that provide adequate prediction capabilities for the occurrence of the noise emissions or for the understanding of acoustic wave travelling in ducts attached with HQ-Tube technique.

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