ICSV14
Cairns • Australia
9-12 July, 2007

14th International Congress on Sound & Vibration

PASSIVE NOISE CONTROL OF A BURNER-COMBUSTOR SYSTEM OF A TURBO-FAN ENGINE

Ayman El-Badawy[1] and Wael EL-ARNA'OUTY[2]

[1]Department of Engineering Mechanics, The German University in Cairo
New Cairo City, Al-Tagamoa Al-Khames, Egypt
[2]Department of Mechanical Engineering, Al-Azhar University
Nasr City, Cairo, Egypt
ayman.elbadawy@guc.edu.eg

Abstract

The application of the Herschel-Quincke (HQ) tube concept as a noise reduction device is employed to reduce the noise of an industrial burner-combustor test rig. A computational technique is developed to design the HQ tube dimensions to control the sound field in such system. Transmission loss predictions from the analytical model are shown to correlate well with experimental data acquired from an extended impedance tube setup, as well as the real test rig. In addition, the frequencies at which maximum attenuation will occur are determined.

1. INTRODUCTION

Noise propagating in a duct is an undesirable effect of many industrial and residential systems that have airflow. HVAC (Heating, Ventilating, and Air Conditioning) systems, gas-turbine generators, exhaust stacks and turbofan engines are some examples of such noise propagation systems.

Turbofan engine noise is produced from different parts of the engine as well as from the turbulence due to the airflow. Each noise component produced by the different parts of the engine has an impact on the overall generated noise depending on the type of turbofan considered. Figure 1 is a representative of the noise distribution components for typical aircraft. The importance of engine noise, in particular the fan and jet exhaust noises, is clearly depicted. Combustion noise also presented in figure 1 is a significant contributor to total aircraft noise [1].

Measurement of combustion noise is made difficult by the fact that both jet noise and combustion noise exhibit broadband spectra and peak in the same frequency range. Since in-flight reduction of jet noise is greater than that of combustion noise, the latter can be a major contributor to the in-flight noise of an aircraft but will be less evident, and more difficult to measure, under static conditions [2].

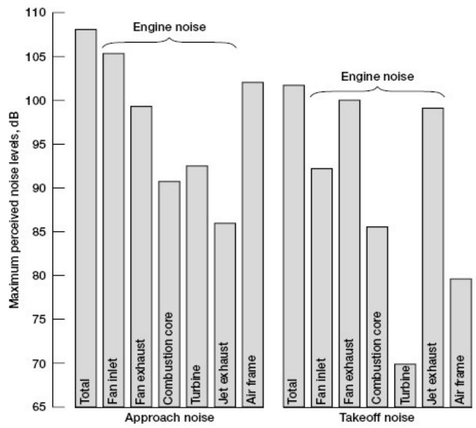

Figure 1. A breakdown of the noise components of a typical engine [1]

In the last few decades, various attempts have been made to reduce the noise from turbofan engines. Figure 2 shows a schematic of a typical High-Bypass Turbofan engine [3] showing the different components including the burner-combustor system. Noise control strategies of turbofan engines can be characterized as active, passive, or a combination of both passive and active approaches. A number of investigations have addressed active control of combustion instability, and the exhaust noise from jet engines, and several passive combustion control technologies have focused on emission control.

Active noise control techniques consist of the introduction of secondary noise sources to cancel, suppress, or absorb part of the original sound field [4, 5]. Combustion instabilities and the resulting pressure oscillations that lead to excessive noise could also produce degradation in performance and ultimately excessive vibrations and failure of the propulsion system. With active combustion control, fuel pulses are used to put pressure oscillations into the system. These oscillations, in turn, cancel out the pressure oscillations being produced by the instabilities. Thus, the engine can have lower pollutant emissions as well as long life [6].

Passive noise control techniques generally consist of either the absorption or the reflection of the original sound field. Absorptive techniques consist of lining a duct with sound absorbing materials, also called liners [7]. The thickness of the liner is related to the range of wavelengths to be attenuated. With increasing thickness, a liner will be able to attenuate longer wavelengths, i.e. lower frequencies. For this reason, liners are normally used for high frequency broadband disturbances, which consist of mainly higher order modes.

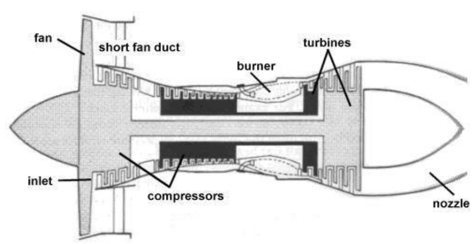

Figure 2. High-Bypass Turbofan [6]

Another passive combustion control technique for turbine engine noise reduction is to use porous matrix insert in turbine engine combustors. This technique has shown to produce a uniform temperature distribution, reduced emissions, as well as elimination of hot spots. Techniques like this have an impact on noise reduction as well because they also address some of the factors that lead to excessive combustion-generated noise, thereby reducing the audible noise spectrum from turbine engines used for propulsion of aircrafts. Since they do not require elaborate sensors and actuators and feed back control systems, the modifications to be implemented will be simple, cost-effective and reliable [8-10].

2. HERSCHEL-QUINCKE TUBE SYSTEM THEORY

Reactive techniques consist of changes in the duct geometry, which result in a reflection of part of the original sound field back toward the noise source. These reactive devices include, but are not limited to, expansion chambers, Helmholtz resonators, and Herschel Quincke tubes. All of these techniques are typically used for lower frequency disturbance applications, which consist of the plane-wave mode [11].

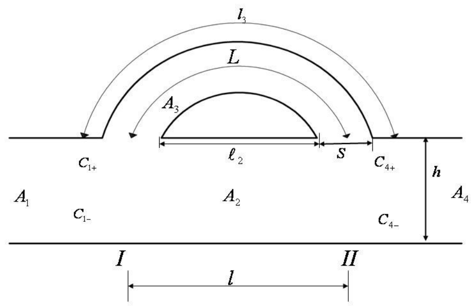

Fig.3. Herschel – Quincke tube

A Herschel-Quincke (HQ) tube [12] is essentially a hollow side-tube that travels along a main-duct axis and attaches to the main-duct at each of the two ends of the tube, as shown in Figure 3. In general, an incident plane-wave acoustic wave, traveling to the right, encounters a branch in the path at the first intersection of the side-tube and main-duct, named the inlet of the HQ tube. The incident wave divides and will later recombine at the second intersection of the side-tube and main-duct, similarly named the outlet of the HQ tube. A difference in path length will create a phase shift between the recombined signals and consequently attenuation of sound will occur at a number of discrete frequencies. Changing tube parameters such as length (l3, S), and the distance between inlet and outlet openings, termed the interface distance (l2), the frequencies of cancellation can be adjusted.

3. ANALYTICAL TREATMENT

A disturbance noise field is assumed to propagate within a two-dimensional duct of height h in the positive x-direction. The pressure due to the disturbance along the duct can be found assuming that the system can be modeled as an infinite rigid-walled duct as shown below in Figure 4.

The pressure due to the disturbance p_D at any point in the duct, $\vec{r} = (x, y)$ can be expressed as the sum of set of N_D modes of order μ propagating in the positive direction. That is

$$P_D \quad (r^{\rightarrow}, t) = \sum_{\mu=0}^{N_D} A_\mu \phi_\mu (k_\mu y) e^{i(\omega t - k_x x)} \tag{1}$$

Where A_μ is the known complex amplitude of the μ^{th} mode (with μ = 0 representing the plane-wave mode), $\phi_\mu(.)$ is the eigenfunction or duct mode, and k_μ is eigenvalue given as:

$$\phi_\mu(k_\mu y) = \cos(k_\mu y); \qquad k_\mu = \frac{\mu\pi}{h} \tag{2a, b}$$

In figure 4, the eigenfunctions are plotted for modes μ=0, 1, 2, 3, and 4, respectively. The positive and negative signs represent the instantaneous positive and negative acoustic pressure fluctuations.

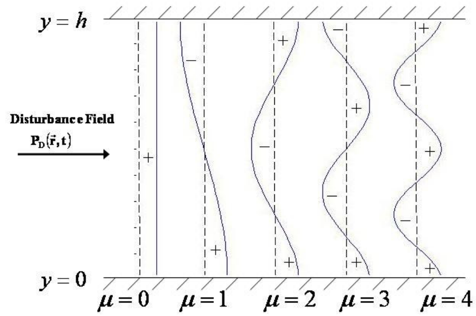

Figure 4. Eigenfunctions $\Phi(\kappa_\mu y)$ for μ = 0, 1, 2, 3, and 4

The propagation characteristics of the modes are given by the axial wave number kx, which is given by

$$k_x = \begin{cases} \sqrt{k^2 - k_\mu^2}, & k > k_\mu \\ -i\sqrt{k_\mu^2 - k^2}, & k < k_\mu \end{cases} \tag{3a, b}$$

where $k = \omega / c$ is the free-field wave number and c is the speed of sound. A mode will propagate for $k > k_\mu$ and will decay when $k < k_\mu$. The frequency at which this change in propagation characteristic occurs is termed the cut-off frequency for mode μ. It is given for $k = k_\mu$ yielding:

$$\omega_\mu(rad/s) = \frac{c\pi}{h}\mu, \qquad \mu = 0, 1, 2, 3, \cdots \tag{4}$$

In equation (1), only propagating modes that satisfy the condition in equation (3a) are assumed in the disturbance at each frequency [11].

The application of these HQ tubes as a noise reduction device has been previously studied. A recent theoretical treatment, for the basic HQ system with a plane-wave sound field, was derived by Selamet, et al [12].

4. DUCT MODEL

The geometry of a Herschel-Quincke tube is shown in figure 3. A is the pipe cross section area, C is the amplitude of pressure oscillation, and the subscripts + and – denote propagation in the positive and negative directions, respectively. From pressure equality at junctions I and II, and conservation of volumetric flow, the ratio of any two fluctuating pressure components can be determined. The transmission loss, which is a measure of the effectiveness of the HQ tube as a noise control device, is then obtained from the ratio of the incident and transmitted waves as:

$$TL = 10\log_{10}\left|\frac{C_{1+}}{C_{4+}}\right|^2 \tag{5}$$

For an anechoic termination, no reflected waves are present in the exit duct. The transmission loss is then given by [12]:

$$TL = 10\log_{10}\left|-\left(\frac{A_2}{A_1}\alpha_2 + \frac{A_3}{A_1}\alpha_3\right) + \frac{\left[1+(A_2/A_1)\phi_2 + (A_3/A_1)\phi_3\right]^2}{4\left[(A_2/A_1)\alpha_2 + (A_3/A_1)\alpha_3\right]}\right|^2 \tag{6}$$

where

$$\alpha_j = \frac{e^{-ikl_j}}{1-e^{-2ikl_j}}, \phi_j = \frac{1+e^{-2ikl_j}}{1-e^{-2ikl_j}} \tag{7a, b}$$

Which exhibits several resonances for a chosen configuration. The frequencies of optimum attenuation are obtained from [12]:

$$\sin(k\ell_3) = -\frac{A_3}{A_2}\sin(k\ell_2) \tag{8}$$

The significance of this expression is that for a fixed set of HQ tube parameters, e.g. l_3, l_2, and S, Equation (8) shows that each mode has a set of optimum frequencies of attenuation. The left hand side of the equation depends only on the tube length. The right hand side of this equation is a function of the tube cross-sectional area, distance between interfaces, and pipe cross-sectional area. The frequency of optimum attenuation occurs when the left and right hand side curves intersects.

5. EXPERIMENTAL SETUP

Figure 5 shows the rig used to test the effect of the HQ tubes on the sound pressure level of the combustion process. The setup consists of combustor section with an inner diameter of 16 cm, and length of 80 cm. The combustor section is designed such that it can be either water cooled or air-cooled. The setup also includes a centrifugal fan, an electric heater, a butterfly valve and an orifice.

In this setup, the combustion noise is much more prominent than the fan/airflow noise. Figure 6a shows Sound Pressure Level (SPL) spectrum measured without the combustion process, while figure 6b shows SPL spectrum measured with the combustion process. These figures show that the SPL of the system with combustion is higher by more than 50 dB than without the combustion process. This illustrates that the flame noise is the main source of noise for our test rig.

Ranges of experiments for different combinations of airspeeds with air/fuel ratios were executed. In the experiments, the air was mixed with commercial liquefied petroleum gas (Butane 70 % and Propane 30 %). The gas was injected through a four tangential tubes to initiate swirling motion. The range of airspeeds used varied from 10 to 32 m/s. The range of air/fuel ratios employed varied from rich mixture (Φ = 1.2) to a lean mixture (Φ = 0.6). We note that the highest sound pressure level peak amplitude happened at an airspeed of 25 m/s and Φ=0.8.

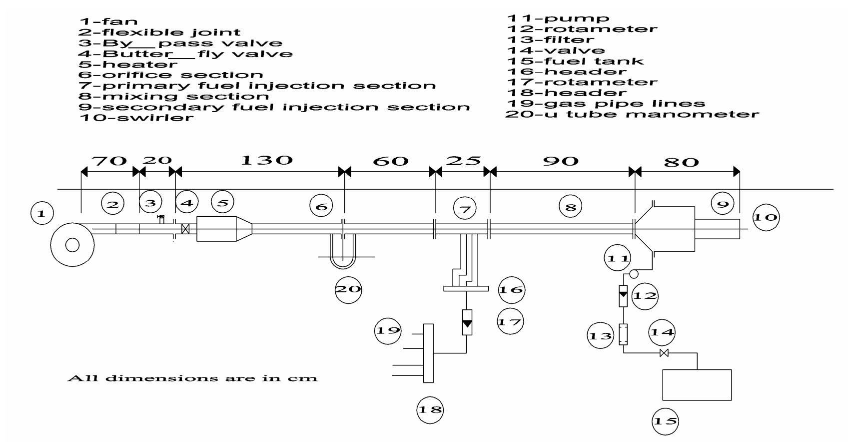

Figure 5. Schematic diagram of the burner-combustor system.

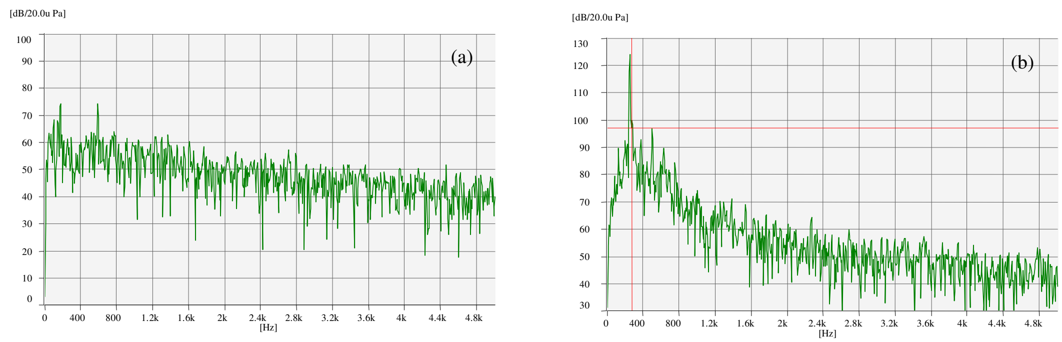

Figure 6. SPL (a) without combustion, (b) with combustion

At low frequencies, those below the first cut-off frequency of the first mode of the system ($k = k_\mu$, μ=1, f = 1070 Hz) the sound field is one-dimensional and only the plane-wave mode will propagate within the duct. Figure 6b shows that the frequency of interest is 250 Hz which is well below the first cutoff frequency. Therefore, plane wave analysis is enough.

6. NUMERICAL RESULTS

In this section, the numerical results for the HQ tube system are presented. These numerical results are desired in order to explore the physical mechanisms behind the attenuation of sound, in particular the attenuation of plane-wave acoustic mode.

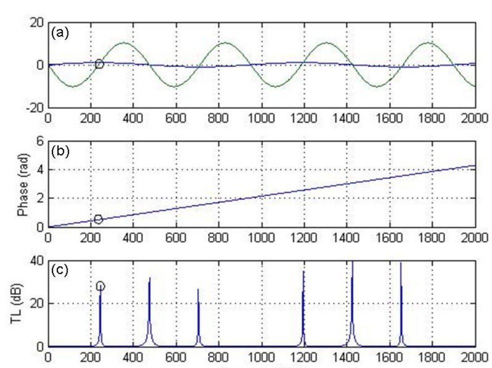

Figure 7. (a) Frequencies of maximum attenuation, (b) Phase difference of recombined waves (rad), and (c) Transmission loss (dB)

Figure 7a shows the left and right-hand side of Equation (8) which predicts the frequencies of maximum attenuation (maximum TL), figure (7b) is the phase difference $kL - k_x l$ between the recombined waves at the second tube-duct interface, while figure 7c is the transmission loss. These curves were produced given the specific combustor dimensions (h =*16* cm), and assuming that there was no fluid flow in the system, but that the fluid is air, i.e. c=*343 m/s* and ρ =*1.21* Ns^2/m^4.

As seen in Figure 7 the frequencies of maximum attenuation occur at the intersections of the two sinusoidal curves. One such intersection has been highlighted and occurs at *245 Hz*. At this frequency the phase difference between the recombined waves is *0.54 rad.*

To verify the performance of the numerical results produced before implementing it on the real burner, the HQ tube dimensions designed in the previous section was implemented on a PVC pipe. The dimensions of the system are h =*16* cm, S =*5 cm*, l_3=*0.72 m*, and l_2=*0.36 m.*

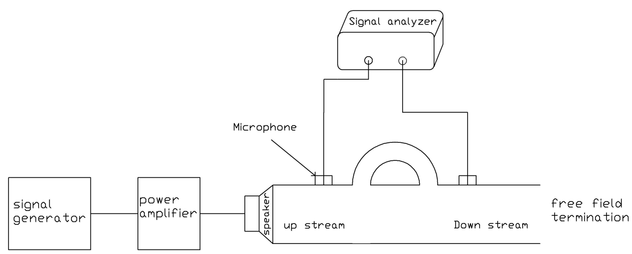

Figure 8. Experimental setup to verify numerical analysis

The setup shown in figure 8 consists of the following: (a) signal generator, (b) loudspeaker with audio amplifier, (c) Herschel-Quincke tube, (d) signal analyzer with microphone input at upstream and down stream signal, and (e) free-field termination to ensure that no waves are reflected back to the acoustics element.

Figure 9 presents the experimental results for the plastic pipe case with a frequency of excitation of 250 Hz, which is similar to what we captured at the real burner-combustor system. It is clear from the figure that a reduction in noise of about 20 dB was realized.

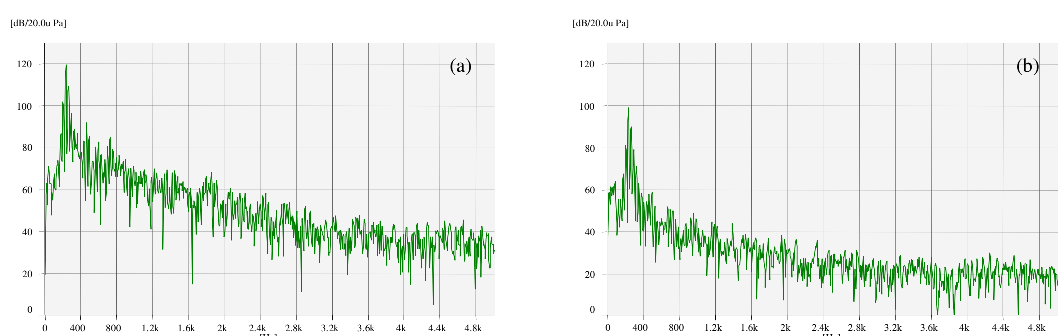

Figure 9: SPL (a) before and, (b) after HQ tube of the PVC pipe setup

7. EXPERIMENTAL RESULTS

To verify the occurrence of sound pressure drop on the real combustor, six HQ tubes with the same dimensions as per the design were fabricated and fitted along the circumference on an exactly similar burner dimensions. Figure 10 shows the SPL spectrum before and after the installation of the HQ tubes. The figures show a drop of about 10 dB in the overall SPL.

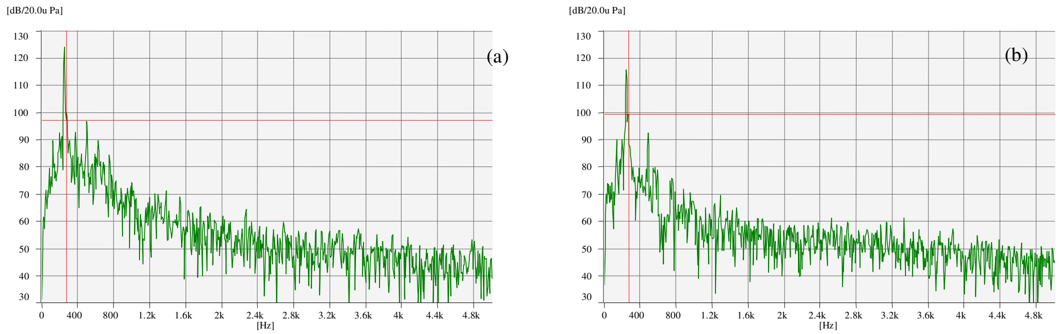

Figure 10: SPL (a) before and, (b) after HQ tube of the test rig

8. CONCLUSIONS

The application of the Herschel-Quincke (HQ) tube concept as a noise reduction device was employed to reduce the noise of an industrial burner-combustor test rig. A computational technique was developed to design the HQ tube dimensions to control the sound field in such system. Transmission loss predictions from the analytical model were shown to correlate well with experimental data acquired from an extended impedance tube setup, as well as the real test rig.

REFERENCES

[1] http://www.nasa.gov/centers/glenn/pdf/84790main_fs03grc.pdf.

[2] *Proceedings of the National Conference on Noise Control Engineering* (NOISE-CON 87), 8-10 June 1987 (A88-39701 16-71), PA, USA, pp 129-134.

[3] http://www.aerospaceweb.org/question/propulsion/q0033.shtml.

[4] Bies, A. David, Hansen, H. Colin, *Engineering Noise Control Theory and Practice* (New Yory: E & FN SPON), 1998, NY, USA, pp. 470-472.

[5] M.O. Tokhi, R.R. Leitch, *Active Noise Control, Clarendon Press, New York,* 1992.

[6] http://www.grc.nasa.gov/WWW/RT2002/5000/5530delaat.html

[7] Harris, A. David, *Noise Control Manual: Guidelines for Problem Solving in the Industrial/Commercial Acoustical Environment*, Van Nostrand Reinhold, New York, 1991.

[8] J.J. Witton, E. Noordally, "Porous media burners for clean engines", *Combustion Processes in Propulsion*, Academic Press/Elsevier, 2005, pp. 139-144.

[9] J.L. Ellzey, A.J. Barra and G. Diepvens, "Simulation of a porous burner for a gas turbine", *Combustion Processes in Propulsion*, Academic Press/Elsevier, 2005, pp. 1455-156.

[10] S. Singh, and R.E. Peck, "An innovative method for reducing gaseous emissions from power turbine combustors", *Advances in Chemical Propulsion*, CRC Press, 2002, pp. 463-476.

[11] L.E. Kinsler, A.R. Frey, A.B. Coppens, and J.V. Sanders, J. V., *Fundamentals of Acoustics*, John Wiley & Sons, New York, 1999.

[12] A. Selamet, N.S. Dickey, and J.M. Novak, "The Herschel-Quincke tube: a theoretical, computational and Experimental investigation", Journal of Acoustical Society of America, Nov. 1994, **96**, No. 5, pp. 3177-3185.