

NOISE AND VIBRATION DIAGNOSTIC AND CONTROL IN AEROSPACE VEHICLES

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1 INTRODUCTION

Noise inside the passenger airplane impacts passenger comfort and crew communication. Prolonged exposure to high noise levels may cause permanent hearing loss and the airlines/operators are liable to damages. However, any noise control effort by adding treatment to the aircraft has associated penalties in terms of payload, range and cost. There are no regulatory interior noise requirements, but mostly result from passenger comfort, noise exposure and economic considerations.

The noise levels in the forward section are generally lower compared to aft section of the airplane. The interior noise control treatment is designed to provide a slow varying noise environment in the cabin. The airplane acoustical models, based on Statistical Energy Analysis (SEA) and Finite-Element Method (FEM), are built and unitized to select treatment to maximize noise benefit with minimum weight and cost penalties. During the design and production stages, noise engineers have more treatment options; however, they are generally left with add-on treatments at the later stages. In fact, for certain noise control treatments retrofitting may not even be feasible or economically viable, except during a major service.

During the testing phase or in-service noise and vibration concerns, noise engineers have the difficult task of identifying offending noise sources and/or their transmission paths. Once the source is identified, generally treating the source is more weight- and cost-effective rather than devising a global treatment or masking the noise. In this paper, common noise sources and diagnostic techniques are discussed through several case studies.

2 NOISE AND VIBRATION SOURCES

Airplane interior noise is a cumulative effect of several aerodynamic and noise and vibration sources, i.e., turbulent boundary layer over the fuselage surface, Environmental Control System (ECS) or air-conditioning, engines, hydraulic motors to drive airframe components, on-board equipment (Examples: Galley chiller, fans, etc.), and special mission equipment for military airplanes.^{1,2} Noise from these sources enter the cabin and flight deck through air path, and is classified as "Airborne", whereas the noise radiated inside from fuselage vibrations is termed as "Structure Borne." A good example of structure borne noise is fuselage vibrations caused by slight engine unbalance.

2.1 Boundary layer noise from turbulent air flow over the fuselage

Boundary layer noise is created by pressure fluctuations in the turbulent airflow over the fuselage surface. Noise characteristics, i.e., amplitude and frequency content from this most significant noise source depend on airplane speed, altitude, and the fuselage station. In the front of the airplane, the boundary layer is thin (i.e., the length scales are small) and high frequencies dominate the noise. The boundary layer becomes turbulent and is thicker towards the back of the airplane and lower frequencies are dominant.

2.2 The Environmental Control System (ECS) and equipment cooling

The airflow through the airplane's ECS creates turbulence due to duct branches, orifices in the duct, bends and outlets. This turbulence generated noise travels along the duct and enters the airplane cabin through the duct openings. The turbulence may also excite duct walls that radiate noise in the cabin. Increased ECS flow rates may be required for cooling requirements associated with special mission equipment or flight deck avionics cooling. The noise increases with flow rate in the ECS duct, therefore, the noise plays an important role in limiting flow velocities. In some cases, additional fans are needed for equipment and avionics cooling that add to the cabin/flight deck noise environment.

2.3 Engine related noise

Engine noise includes buzz-saw noise and exhaust noise forward and aft of the engine and Engine Vibration Related Noise (EVRN) near the wing or aft cabin (for fuselage mounted engines). Engine buzz-saw is transient noise, as it is heard during take-off and climbs.¹ Exhaust noise is heard as a low frequency noise rumble in the passenger cabin. Airplane makers and engine companies have been successfully controlling engine exhaust noise by developing and integrating treatments in new engine designs. Additional noise reductions are achieved by extra treatment in the airplane sidewalls resulting in weight penalties.

EVRN results from slight imbalances in low- and high pressure turbine rotors at spool frequencies. These low-frequency sound are heard at low engine speeds (i.e., at low altitudes when fuselage modes coincide with spool frequencies) in the forward part of the airplane (for wing-mounted engines) and in the aft cabin (for aft-fuselage mounted engines). During lift-off of the launch vehicle, engine noise may also impact payload inside the fairing.¹

2.4 On-board equipment and other noise sources

Noise generated by on-board and special mission equipment in the main- and lower-decks, and other mechanical equipment (such as hydraulic equipment that are needed for flight operations during take-off and landing, i.e., landing gear deployment, outflow valve operation, etc.) contribute to interior noise. Air leakage through doors can also impact the noise environment. Some of these noise sources may be short duration and may be considered as transients. However, very high noise levels or continuous noise sources may need to be addressed.

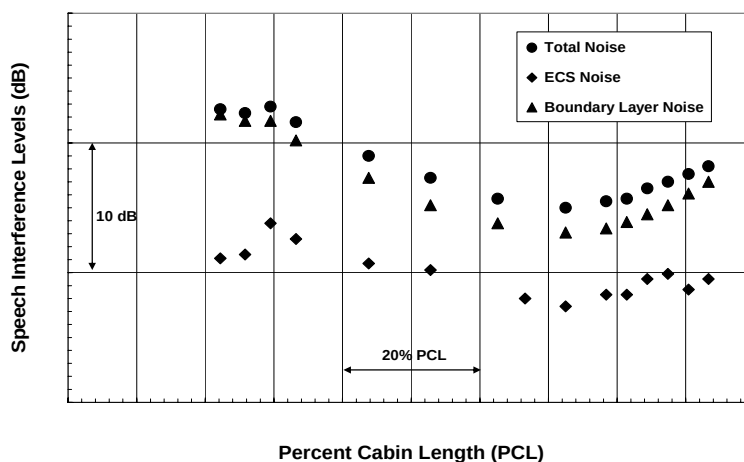


Figure 1: Boundary layer and ECS noise components

3 DIAGNOSTIC TECHNIQUES

Flight test validation of the design is one of the crucial steps in any new airplane program. Various analysis tools available for acoustic treatment design, e.g., SEA and FEM codes are frequently calibrated with flight test data; still the treatment design may require some adjustments during the validation flight tests. Ironically, as discussed earlier the noise engineers may not have all the treatment options available, as during the design stage. Noise treatment globally installed across the airplane, e.g., thickening or increasing density of insulation blankets may not even address a particular area of concern. Therefore, it is necessary to identify the problem source or its transmission path for a most cost- and weight effective solution. Noise levels of 2-3 dB above the background noise are detectable by the human ear and if the source is highly localized, then a subjective evaluation of the cabin might give some indication of the source location.

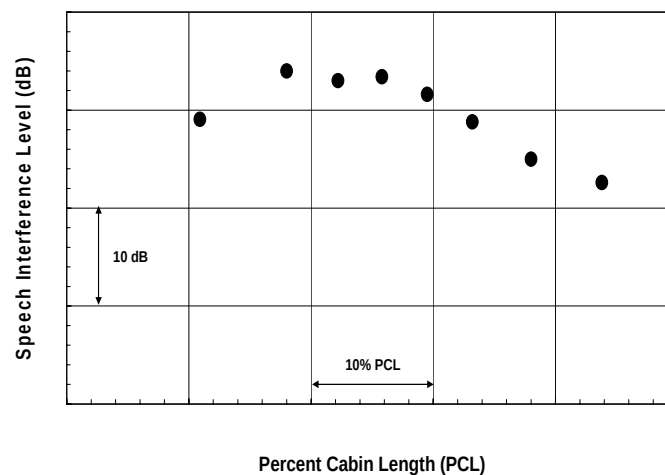


Figure 2: Noise measurements at standing height at a typical cruise condition

A cabin noise survey along the airplane using microphones installed on passenger seats is normally conducted during the flight test program on the ground and at take-off, landing and cruise conditions. If the noise levels exceed the customer requirements or the airplane noise specifications, a noise engineer is entrusted with a difficult task of identifying the noise source(s), treatment design and implementation, and the flight test validation. The following techniques are helpful in noise source and transmission path identifications. a) Source separation, b) Detailed spectral analysis, c) Sound intensity scans, d) Noise blocking panels, e) Skin panel or equipment acceleration spectra.

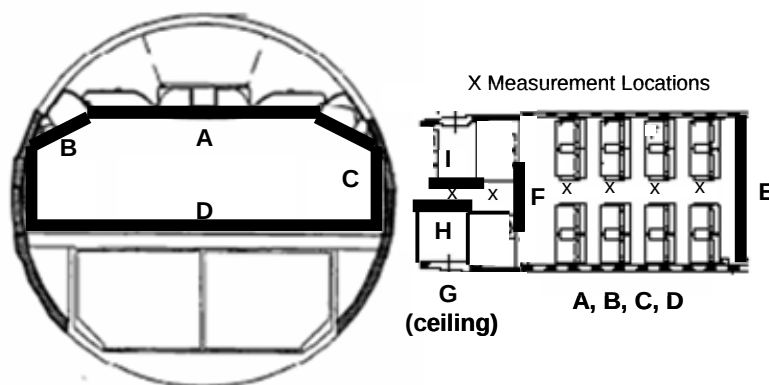


Figure 3: Noise blocking panel and measurement locations

Figure 1 shows higher Speech Interference Levels (SILs) in the forward cabin of an airplane. Noise levels at higher frequencies or SIL are generally related to boundary layer noise or ECS. In order to separate noise sources, noise data was recorded at a cruise condition with ECS OFF and the engines at idle. At locations away from the engines, this noise with ECS OFF will be closely approximated by the boundary layer noise. At cabin locations closer to engines i.e., where the data may be affected by the engine noise, additional data at several different power settings will be required to estimate turbulent boundary layer noise.³ The ECS noise component is obtained by subtracting the boundary layer noise component from the total noise. In Figure 1, the ECS noise component is 5-10 dB lower than the boundary layer noise and shows a peak in the forward cabin. The total noise in forward section is only 0.5-1 dB higher than the boundary layer noise. Therefore, the noise reduction efforts were directed to treating only the boundary layer noise source. If the ECS noise is higher or comparable to the boundary layer noise, then the ECS noise must be reduced for any further cabin noise reduction.

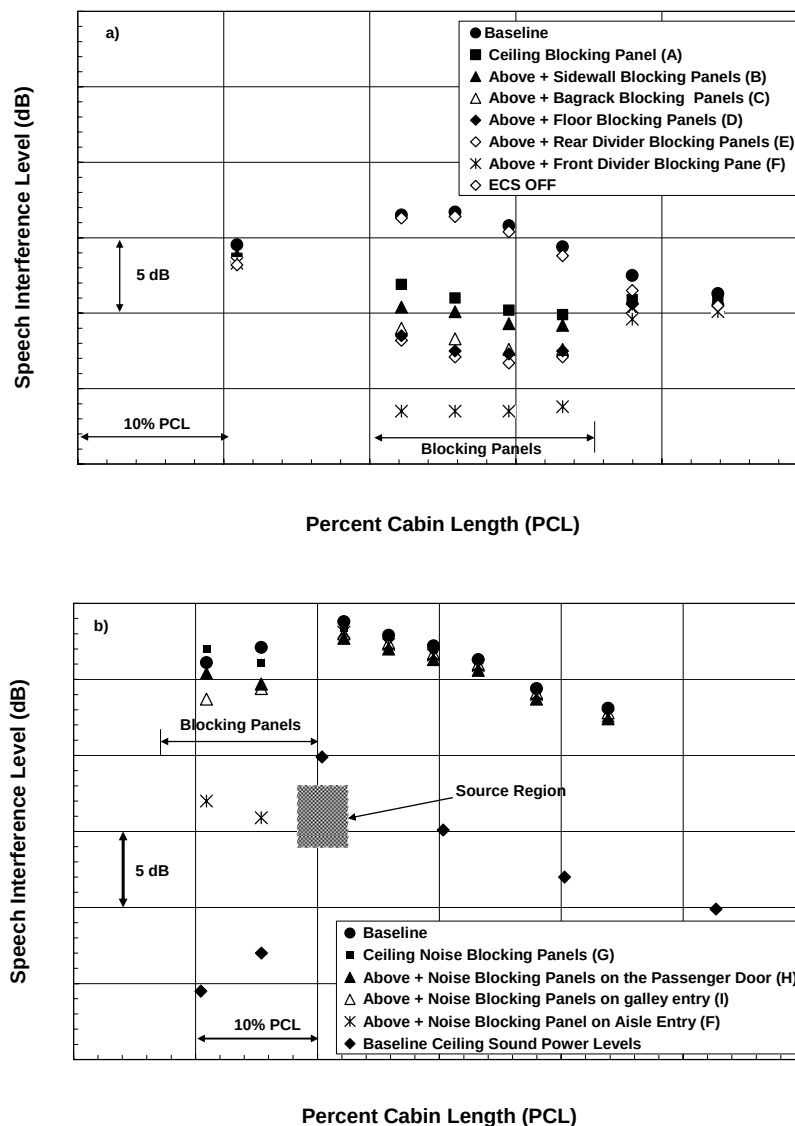


Figure 4. Noise measurements with noise blocking panels at a typical cruise condition

Sound intensity and noise blocking panel methods are very useful source isolation techniques. Sound intensity is the rate of acoustic energy flow and is a vector quantity, i.e., gives the energy flow direction.⁴ This technique uses a dual microphone probe. An alternate to the standard sound intensity technique is acoustic holography,⁵ which uses an array of microphones in a two dimensional surface. As discussed earlier, treating a source is generally the most cost and weight effective resolution to any noise control effort. With the use of sound intensity scans, a cabin location, where acoustic energy enters the cabin can be identified. The test area is divided into several smaller areas (~1 square meter). The actual scanning time depends on the scanning speed, source type and the frequency of interest (e.g., a random source and lower frequencies will require relatively longer scanning time). All test areas are then compared and ranked in the order of acoustic energy entering the cabin (a negative sign will indicate the acoustic energy flow from the cabin).

Noise blocking panels are made from heavy foam or insulation blankets. Interior noise levels are measured after systematically covering the airplane's internal surfaces with these panels. Often noise blocking panel tests are conducted as a precursor to sound intensity, which better defines source areas in order to minimize number of scans. Analysis of signals from accelerometers attached to skin panels and equipment are also used to resolve noise concerns resulting from structural vibrations and on-board equipment. Due to complexities associated with attaching accelerometers to the skin panels, acceleration measurements are not as frequently used.

4 CASE STUDIES AND MITIGATION STRATEGIES

The noise measurements at standing height are shown in Figure 2. The forward cabin noise is dominated by turbulent boundary layer on the fuselage surface. The separation of boundary-layer and ECS components indicated that ECS adds about 1 dB to total SIL (Figure 1). This confirmed that the ECS is not a major noise contributor. Based upon these observations, further diagnostic tests were necessary to isolate the most dominant noise source.

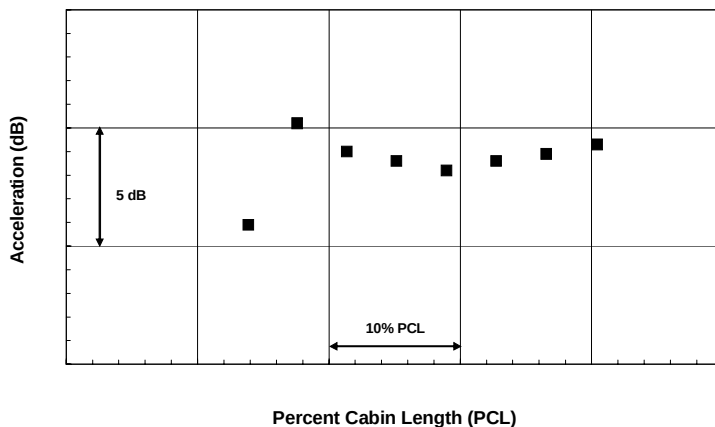


Figure 5. Skin panel accelerations

Six sets of noise blocking panels (A through F, as shown in Figure 3) made from three inch thick foam insulation (providing ~15 dB noise reduction at 1000 Hz) were installed in the forward part of the airplane. The blocking panels were systematically removed, i.e., one at a time and sound pressure levels were measured at standing heights in the aisle and at locations forward of the airplane (i.e., outside the tunnel formed by the blocking panels). Results in Figure 4a show that turning off ECS provided an insignificant noise reduction. The noise blocking panels on the ceiling provided about 5 dB SIL reductions and the sidewalls, stowage bins and the did not appear to be major noise contributors. No appreciable difference was noticed when the aft divider blocking panel,

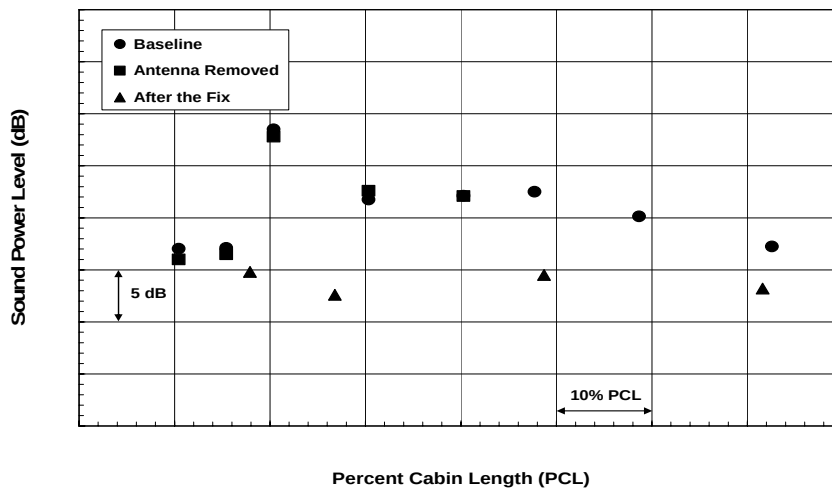


Figure 6. Sound intensity measurements along the cabin ceiling

E was removed, whereas an increase of 5 dB was noticed with the removal of the front divider panel, F. Noise increase, with the removal of panel F, was a little puzzling. Therefore, another test as shown in Figure 3, with four blocking panels (F through I, on the ceiling, passenger door, galley entry and aisle entry) forward of the previous measurement location were installed and noise measurements are shown in Figure 4b. All blocking panels showed a little impact on noise levels, except at the aisle entry, F. When this panel was removed, noise levels in the forward section (in the blocking panel zone as shown in Figure 4b) dropped by over 10 dB.

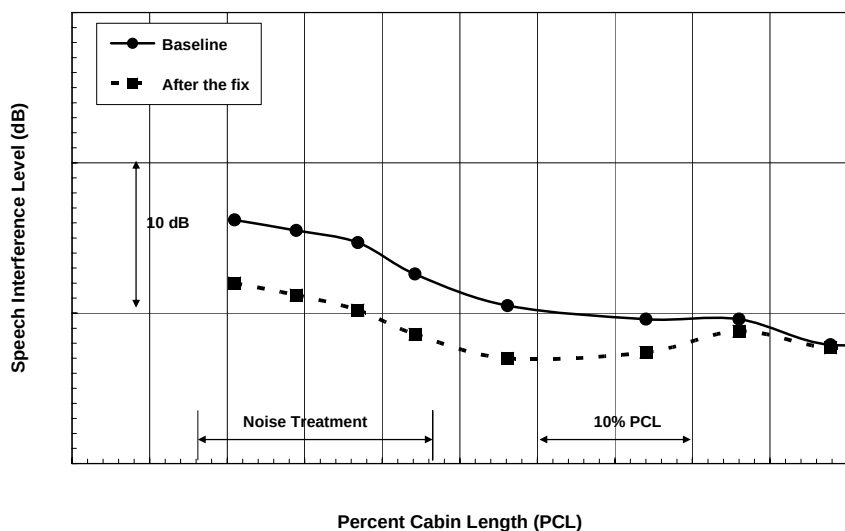


Figure 7. Noise levels before and after the fix

Sound intensity measurements along the cabin ceiling (Figure 4b) and skin panel acceleration measurements (Figure 5) along the length of the airplane showed sudden rise in level by about 10 and 5 dB, respectively. This confirmed the noise source at a location shown in Figure 4b. A visual inspection of the antenna at this location revealed a small step caused by its base plate. This suggested that the antenna installation might be causing flow disturbances locally (and therefore, pressure fluctuations), which may be responsible for high sound pressure levels in the cabin at this

location. Sound intensities at the ceiling in the forward section, baseline and with the antenna removed, did not show any appreciable difference (Figure 6).

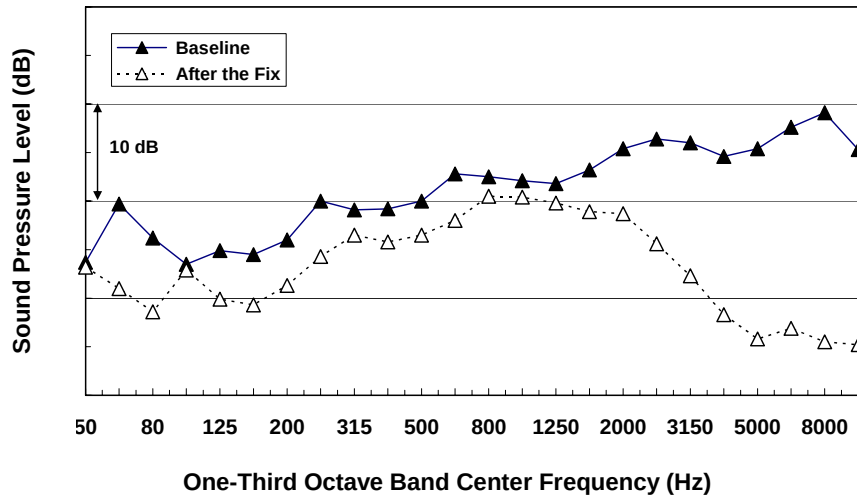


Figure 8. Sound pressure levels under an ECS duct at a typical cruise condition

Skin damping treatment⁶ was applied to fuselage skin panels in the crown area (Figure 7) to treat this noise source. This weight- and cost-effective treatment was very successful in treating the noise source and resulted in 4-5 dB SIL reductions at seated heights as shown in Figure 7. It is noteworthy that SIL reductions continued about 20% cabin length beyond the area where the skin damping treatment was applied. This confirmed the noise source in the forward cabin was responsible for high noise levels due to structural vibrations that were transmitted far in the aft cabin. Sound intensities measurements along the ceiling after installing the damping treatment show very little lengthwise variation (Figure 6).

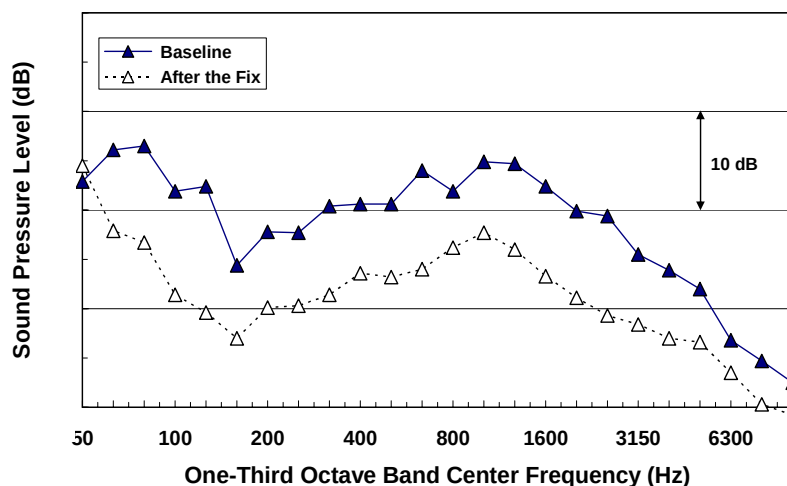


Figure 9. Sound pressure levels in flight deck at a typical cruise condition

Two case studies from ECS and avionics cooling flow noise are shown in Figures 8 and 9. In the first case, noise levels in the forward galley near an ECS flow outlet were 7-8 dB higher. Flow measurements from this outlet indicated 30 - 35% higher than the requirement (noise varies as the

6th power of the flow velocity). To reduce the flow by 30% through the outlet, an orifice was installed in the ECS duct that resulted in 8 dB noise reduction. The orifice location was carefully chosen, such that the orifice generated noise was not impacting the cabin. In the other case, high noise levels in the flight deck on the ground were traced to an avionics cooling fan. The fan capacity was about 40% higher than the cooling flow requirement and an orifice place was used in the exit duct to throttle the flow to the correct flow rate. It was discovered that the orifice was too close to the outlet and the noise reduction due to the reduced flow rate was compensated by the orifice generated noise that propagated through the duct outlet. A muffler used upstream of the fan did not result in any appreciable noise reduction. The exiting fan was replaced with a new lower capacity fan with comparable case radiated noise. The new fan resulted in 7 dB noise reduction in the flight deck. Additionally, this option also resulted in weight savings with the removal of the orifice, muffler and other hardware.

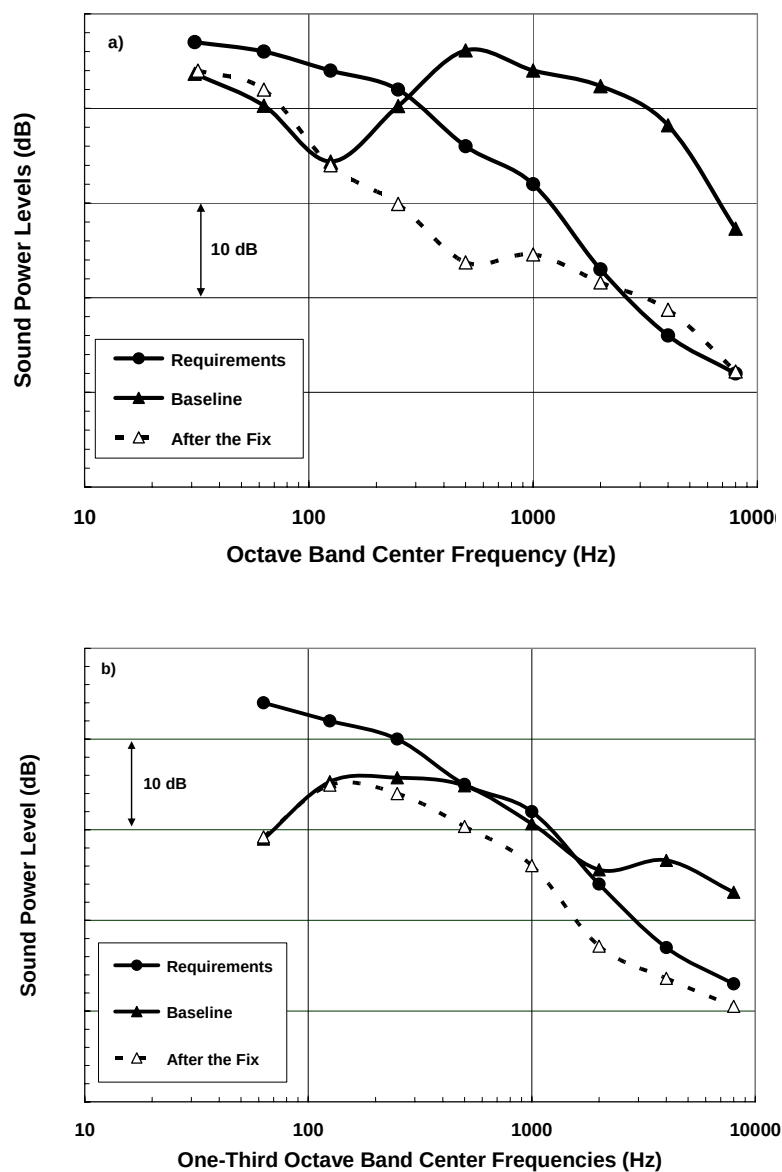


Figure 10. Equipment noise

On-board Equipment cooling fans are often offending noise sources. Noise is generated internally by high flow velocity or flow separation and turbulence through the air flow paths. In a case study shown in Figure 10a, noise levels were 15 dB higher than the requirement. It was obvious that re-design of the flow path to reduce flow separation and turbulence would have not resulted in 15 dB noise reductions and it could only be achieved through significant reductions in the fan speed. In order to keep the same flow, a larger fan with twice the hub-diameter and half the rotational speed was used. The new fan resulted in about 15 dB noise reduction. In the second case, it was not possible to accommodate a larger fan to get about 8 dB noise reductions and the fan was completely removed from the equipment (Figure 10b). The required cooling for the equipment was achieved by using air from the airplane's ECS system.

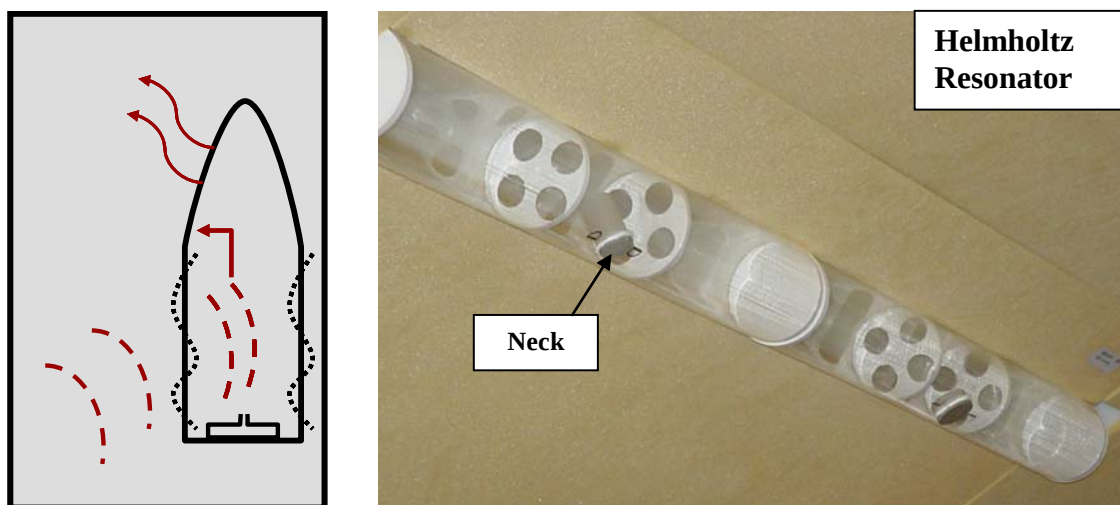


Figure 11. Rocket fairing and Helmholtz resonator⁷

High levels of structural vibrations and noise (generally in 30-100 Hz range) can affect payload inside the space vehicle.⁷ Noise reduction in cylindrical cavities at low frequencies is difficult to accomplish. Helmholtz Resonators (HR) are highly effective at very low frequency noise reductions that are the dominant noise sources during liftoff of vehicles (Figure 11). HR size is comparatively large, but with possible active control smaller size is possible, i.e., with piezoelectric polymer Polyvinylidene Fluoride (PVDF) speakers inside the HR tubes may move air inside the cavity and the size may be reduced.

5 CONCLUDING REMARKS

A review of common noise and vibration sources and diagnostic techniques has been discussed. Several case studies to identify noise sources and their resolution are presented. It is emphasised that treating the source is more cost- and weight effective approach to address noise and vibration concerns.

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