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Reduction of APU Noise By Modifying The Exhaust Pipe Using Open Source Software

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A B S T R A C T

This Study is related to noise reduction in aircraft and an emphasis on the importance of exhaust pipe design for the auxiliary power units. This study it aims to optimize exhaust pipe layouts as a method of minimizing noise emissions using open-source software and computer modelling. One of the most important subjects for research is investigation of expansion chamber as a potential technique to reduce noise. The sound waves will be absorbed and softened by the placement of chambers inside an exhaust system. The main goal of this study is minimizing the auxiliary power unit's noise level to ideally under 85 dB and lead to quieter airports and improved noise footprint for surrounding communities. The simulation in this research succeeded in achieving a noise reduction of up to 14 dB compared to original design which had a pressure noise level of 91 dB, resulting in a final noise level below 77 dB.

تقليل ضوضاء وحدة الطاقة المساعدة عن طريق تحسين تصميم أنبوب العادم باستخدام برامج مفتوحة المصدر

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الملخص

تتعلق هذه الدراسة بتقليل الضوضاء في الطائرات والتركيز على أهمية تصميم أنبوب العادم لوحدة الطاقة المساعدة. تهدف هذه الدراسة إلى تحسين تصميم أنبوب العادم كطريقة لتقليل انبعاثات الضوضاء باستخدام برامج مفتوحة المصدر والنمذجة الحاسوبية. أحد أهم مواضيع البحث هو التحقيق في غرفة التمدد كتقنية محتملة لتقليل الضوضاء. سيتم امتصاص الموجات الصوتية وتخفيفها من خلال وضع الغرف داخل نظام العادم. الهدف هو تقليل الضوضاء، ويفضل أن تكون أقل من 85 ديسيبل مما يؤدي إلى مطارات أكثر هدوء وتحسين الضوضاء للمجتمعات المحيطة. نجحت المحاكاة في هذا البحث في تحقيق تقليل الضوضاء بما يصل إلى 14 ديسيبل مقارنة بالتصميم الأصلي الذي كان مستوى ضوضاء الضغط فيه 91 ديسيبل وتم الحصول على مستوى ضوضاء نهائي أقل من 77 ديسيبل.

1. Introduction

Uncontrolled noise is a pervasive issue across various industries, posing significant threats to human health, comfort, and the environment. Noise pollution can cause hearing damage, disrupt sleep patterns, and even contribute to cardiovascular problems. To the extent feasible, engineering controls, administrative controls, and work practices shall be used to ensure that workers are not exposed to noise at or above 85 decibels (dB) for working time of eight hours [1]. In the aviation sector, auxiliary power units (APUs) are one of the major sources of noise pollution, particularly around airports. This research aims to exploring effective strategies for reducing noise emissions from APU exhaust systems. A new APU exhaust shape will be designed and evaluated with various noise control measures, paving the way for a quieter and more sustainable aviation industry.
Mahadhir Mohammad, Megat Muhammad Asyraf Buang, Afiq Aiman Dahlan, Muhammad Hariz Khairuddin and Mohd Farid Muhamad Said [2] investigated the use of GT-Power simulation software to analyze the impact of muffler design parameters (perforations, baffles,

pipe diameter and size) on noise reduction in an automotive exhaust system. The focus on achieving noise reduction while minimizing backpressure is a valuable approach.
Fangsen, Ying and Richard Chao [3] explored a hybrid muffler design that combines reactive and dissipative elements for improved broad-band noise reduction. Boundary Element Method (BEM) and software like ANSYS and SYSNOISE were employed in this study to perform muffler modeling and acoustic analysis. This facilitated parametric studies, enabling the exploration of various design factors. The impact of different parameters, including chamber dimensions, and flow resistivity, on the muffler's Transmission Loss (TL) across a frequency range was also investigated.
Niloofar Damyar, Fariba Mansouri, Ali Khavanin, Ahmad Jonidi Jafari, Hassan Asilian-Mahabadi and Ramazan Mirzaei[4] designed a double-expansion chamber muffler (as shown in figures 1 & 2) without baffles, sound-absorbing material in small size ,lightweight and with equal-length chambers based on theoretical equations and the

transfer matrix (TM) approach. TL was measured across a broad frequency range (63 - 6300 Hz) using an impedance tube and microphones. The measured TL was compared with theoretical predictions obtained from design equations.
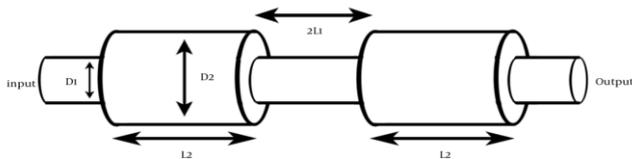

Fig. 1 **:**Schematics of two-chamber expansion chamber mufflers with external coupling tube

Fig. 2 **:**View of the experimental setup for measuring TL; right, low frequencies; left, high frequencies

2. Auxiliary Power Unit Of A320

APU is a gas-turbine engine that is typically installed in the tail section of the aircraft A320. This location allows for easy access to the APU for maintenance and servicing while minimizing its impact on passenger and cargo space. The airbus 320 family typically houses a Honeywell 131-9A APU. The APU is responsible for providing pneumatic and electrical power during ground operations, also serves as a backup source of power during emergencies in flight. The APU compartment consists of various subsystems essential for its operation as engine, generator drive, ignition system, accessory gearbox, fuel system, air inlet, exhaust system and control system.

Like any jet engine, the APU is a source of airport noise pollution [5], particularly during ground operations. Due to the proximity of passengers and airport personnel to the APU during operation, noise reduction is a critical concern. This noise can be annoying to maintenance engineers, passengers and crew, cause hearing losses and sleep disruption, can affect the environment and cause noise pollution and community annoyance. APU noise originates from several sources. It comes from the turbine blades and air intake/exhaust. To address this, quieter exhaust pipes with new designs and technologies are being developed. To minimize noise pollution, the focus is on developing quieter exhaust pipe designs through implementing design enhancements and innovative technologies. Exhaust noise is one of the most important problems associated with the operation of APUs.

3. Current Suggested Method For Reducing The Auxiliary Power Unit Noise

While engine noise reduction methods provide valuable insights, APUs present unique challenges due to their size and operational characteristics. However, some of the principles can be adapted for APU noise control. Edoardo Alessio Piana, Ulf Erik Carlsson, Adriano Maria Lezzi, Diego Paderno, and Susann Boij explore noise generation by the source and its propagation within ducts before radiating outwards [6]. Their research details the different mechanisms that generate noise in ducts, including those related to rotating machinery, vibrating membranes, vortex shedding, and turbulence. They studied the effects of expansion chambers, quarter-wave resonators, and Helmholtz resonators on transmission losses in ventilation ducts. Additionally, the Transition Matrix Method (TMM) in MATLAB has been used to describe the acoustic properties of the silencer system. This method, based on the same element model, has recently found application in designing exhaust systems for vehicles and other systems. the duct is split into fundamental blocks, each one having an inlet and an outlet. Such blocks can be characterized by different transfer matrices relating two variables: the sound pressure, p, and the volumetric flow rate, Q. Applying an electro-acoustic analogy where the pressure is equivalent to voltage and the volumetric flow, the transfer matrix approach can be considered as the equivalent of the two Kirchhoff's circuit laws. The interconnection of different blocks can be expressed by a product of the different transfer matrices characterizing the single blocks describing the system as shown in

figure 3. Under linear conditions, the T-matrix method can be used to describe the acoustic properties of a silencer system.

$$\begin{Bmatrix} p_{in} \\ Q_{in} \end{Bmatrix} = [\mathbf{T}] \cdot \begin{Bmatrix} p_{out} \\ Q_{out} \end{Bmatrix}$$

Fig. 3 **:**Equivalent acoustic model of a single element—transfer matrix representation
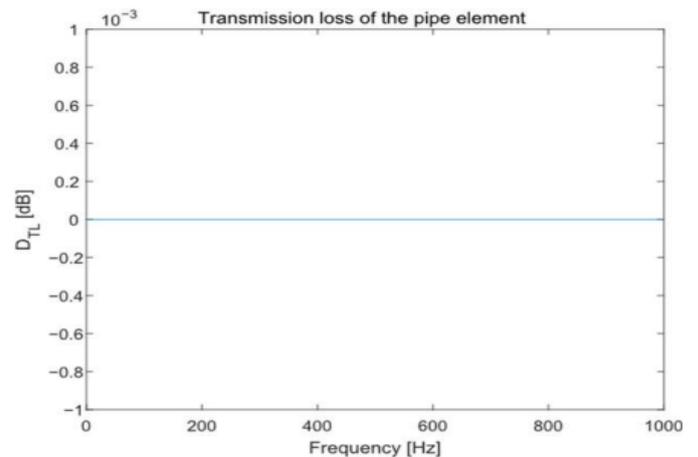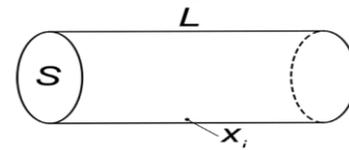

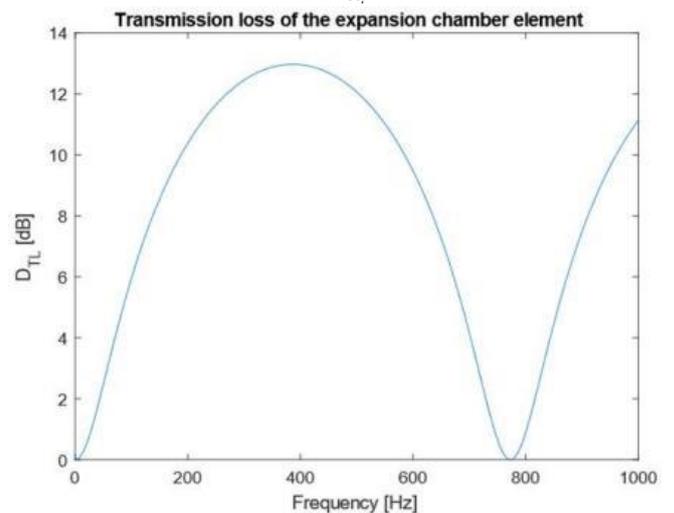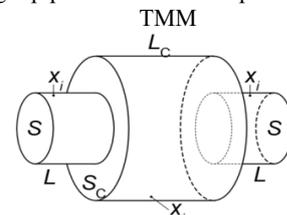**Fig. 4** **:**Straight pipe sketch and example of TL obtained with TMM

Fig. 5 **:**Chamber sketch and example of TL obtained with TMM
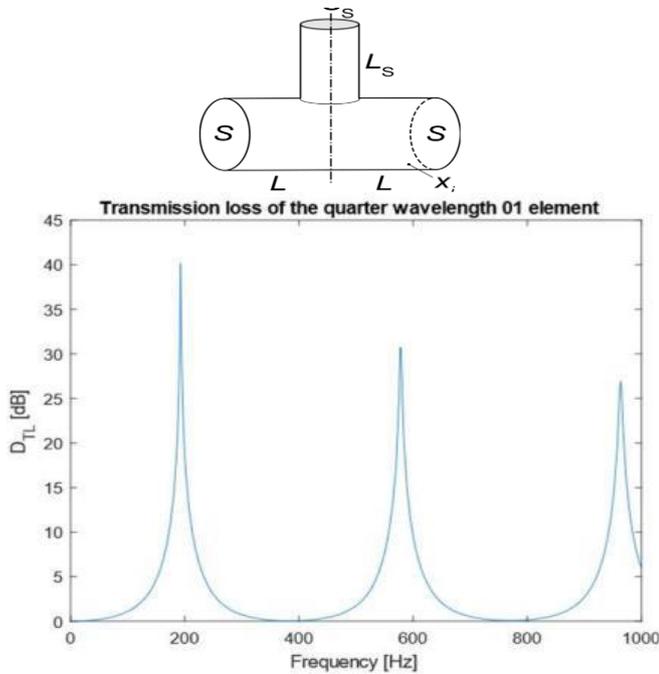
Fig. 6 : Quarter-wavelength resonator sketch and example of TL obtained with TMM

All models described hereafter assume 1-dimensional plane wave propagation along the duct axis. Each block corresponds to a physical component and has a specific effect on the overall sound attenuation of the system. The figures 4-6 show the effect of changing the exhaust shape on transmission loss calculated by TTM wher the transmission loss is defined as the acoustical power difference between the forward travelling incident pressure wave at the inlet of the element and the forward travelling transmitted pressure wave at the outlet of the element. Expressed in decibels, the equation for determining the TL reads:

TL = 10 log W (in) / W (out).

Prasad V. Shinde, P.M. Gavali, R.A. Barawade, Y.B. Mohite, and P.B. Shinde emphasized the importance of well-designed mufflers in controlling noise pollution [7]. They insured that selecting the right muffler depends on various factors like size, material, and noise reduction targets. Muffler design involves optimizing factors such as diameter, length, chambers, internal configuration, and perforation percentage. Their work explores various muffler types, including baffle, resonance, wave cancellation, absorptive, and combination mufflers, highlighting the advantages and limitations of each.

4. Mathematical Modelling Of Sound Waves

Mathematical models act as bridges between reality and mathematics. They translate real-world phenomena into equations, allowing us to predict, simulate, and optimize designs across science and engineering. The governing equations, for a no thermal conduction, no viscosity, adiabatic and reversible, fluid flow problem, are the momentum equation (Euler's equation) and the continuity equation. These are given by [8]:

$$\partial\rho/\partial t + \nabla.(\rho\,v) = 0 \qquad (1)$$
$$\partial v/\partial t + v(\nabla.v) = -\,\nabla p\,(1/\rho) \qquad (2)$$

Where ρ is the total density, p is the total pressure, v is the velocity field. Assumption that the fluctuations in the fluid dynamical quantities are small quantities are expressed as the sum of the mean part and the small fluctuation. These fluctuations of pressure and density waves showed in figure 7, see below.

$$p = p0 + p'(t) \qquad (3)$$
$$\rho = \rho0 + \rho'(t) \qquad (4)$$
$$v = v'(t) \qquad (5)$$

Where 0 indicates a mean value and a prime symbol a fluctuation, The small parameters expansion is performed on a stationary fluid ($v\_0 = 0$). Inserting fluctuations values into the governing equations, retaining terms linear in the acoustic variables yields, the wave equation for pressure waves is:

$$\partial^2\,\rho/\partial t^2 = c^2\,\nabla p^2 \qquad (6)$$

Here c (SI unit: m/s) denotes the speed of sound. This is the most fundamental equation in acoustics. It describes the properties of a sound field in space and time and how those properties evolve.
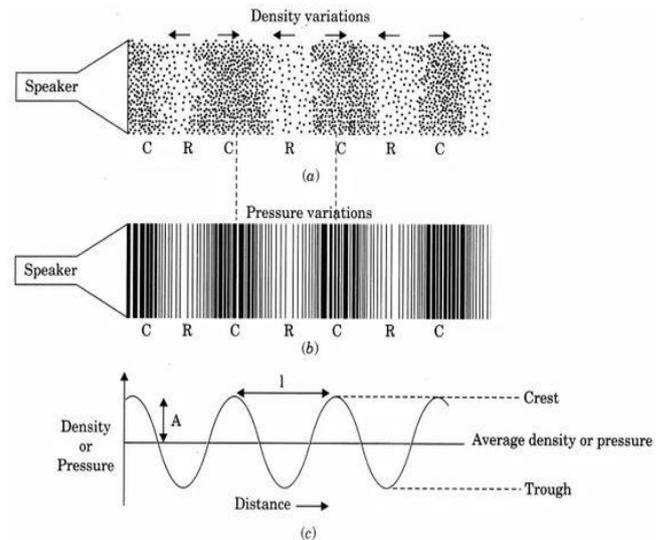

Fig. 7 : Schematic of the fluctuations of pressure and density waves

5. Reflection Of Sound Waves And Expansion Chamber

Sound waves travel through a medium (air, water, solid) as vibrations or pressure disturbances. These vibrations involve the back-and-forth movement of particles in the medium, causing compressions (high-pressure zones) and rarefactions (low-pressure zones) that move outwards from the source of the sound. When the sound wave reaches a boundary, like a wall, some of the wave's energy is absorbed by the barrier, while the remaining energy is reflected back into the medium. The reflected wave travels in a new direction, determined by the angle of incidence (the angle at which the original wave hit the barrier). This follows the law of reflection: the angle of incidence equals the angle of reflection. Constructive and destructive interferences are produced (figures 8-9) by the interference of reflected waves with the incident wave. By understanding how sound waves reflect within the exhaust system, engineers can design mufflers and exhaust components that effectively reduce noise. As a sound waves traveling through the exhaust pipe. These waves encounter a change in the pipe geometry, such as an expansion chamber. When the sound waves reach this change in geometry, some of the wave energy is reflected back into the exhaust pipe. The reflected wave interacts with the original sound wave still traveling forward. If certain conditions are met, these two waves can be out of phase. This means the peaks of one wave coincide with the troughs of the other. When two sound waves are out of phase, they partially or completely cancel each other out. This phenomenon is called destructive interference as shown in figure 9. In the exhaust system, the reflected wave, depending on its timing and amplitude, can cancel out some of the sound energy of the original wave, leading to a reduction in the overall sound pressure level.
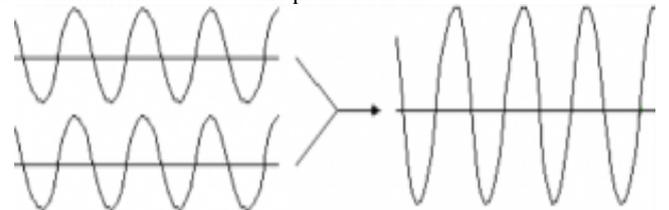

Fig. 8 : In-phase waves combination, constructive interference produces a wave with greater amplitude.
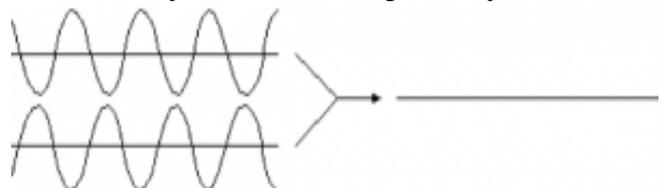

Fig. 9 : Out-phase waves combination, destructive interference produces a wave with less (or no) amplitude.
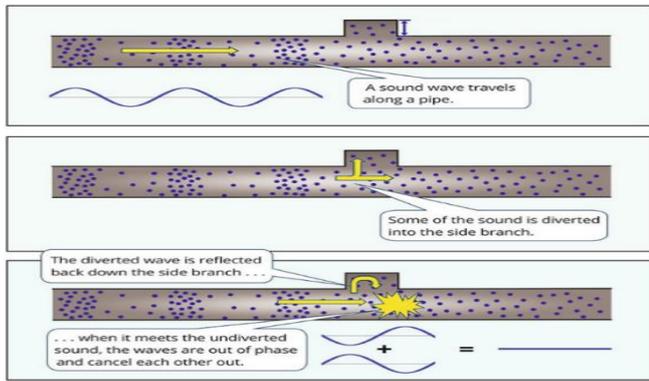
Fig. 10   : The effect of reflected sound waves in exhaust.

Expansion chamber features an area expansion followed by an area contraction, resulting in a double reflection of sound waves. Then the reflected waves with incident wave cancel each other out. The expansion chamber muffler is a reactive-type muffler, because the reduction of noise transmission through the muffler is achieved by reflecting back to the source a portion of the energy entering the muffler. The expansion chamber muffler consists of one or more chambers or expansion volumes, which act as resonators to provide an acoustic mismatch for the acoustic energy being transmitted along the main tube. The attenuation depends on the inlet/outlet cross section areas, main chamber cross section area, and the length of the expansion chamber and position.

6. Modified Geometry Of Exhaust Pipe Of Auxiliary Power Unit

The original pipe, based on the Honeywell 131-9A as shown in figures 11-12 , has a length of 1.54 meters, an inner diameter of 0.24 meters, and a wall thickness of 0.001 meters, all made from titanium.
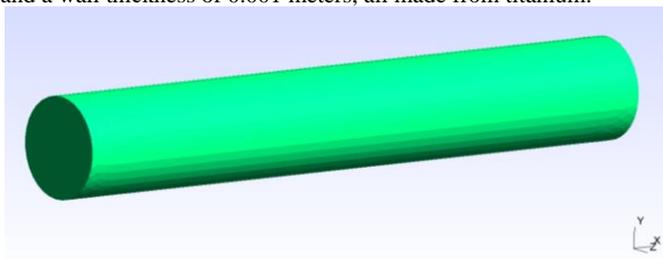

Fig. 11   : Overview of the APU exhaust pipe 3-D model
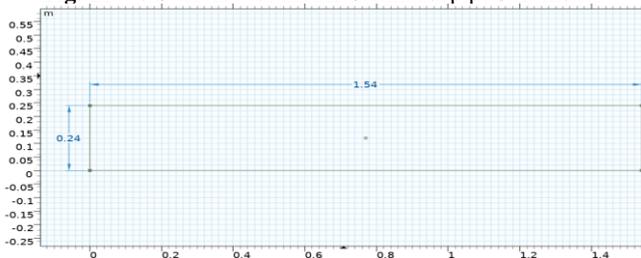

Fig. 12   : Dimensions of exhaust pipe

The key modification involves adding one or two strategically placed expansion chambers within the exhaust pipe. It achieves this by having an area expansion followed by an area contraction. The available space between the muffler and the tail cone wall is limited (32 cm at the inlet, 16 cm at the outlet). This restricts the size of the expansion chamber that can be implemented. The idea is to find a balance between chamber size and its noise reduction capabilities. While a larger chamber generally offers better noise reduction, a smaller, strategically designed chamber can still be effective.

Two configurations are being explored to achieve noise reduction within the available space:

1. Exhaust Pipe with One Expansion Chamber

This design integrates a single, large chamber. The chamber length is 0.48 meters (twice the diameter of the base pipe) with diameter 0.48 meters (twice the diameter of the base pipe) positioned close to the beginning of the base pipe, approximately 0.05 meters away (3.3% of the total pipe length); all this showed in figures 13-14.

2. Exhaust Pipe with Two Expansion Chambers

This design incorporates two smaller chambers within the exhaust pipe, each chamber will be has 0.24 meters Length (equal to the

diameter of the base pipe) and 0.48 meters diameter (twice the diameter of the base pipe), see figures 15-16. The first chamber will be positioned similarly to the single chamber configuration (0.05 meters from the beginning) and the second chamber will be placed downstream of the first chamber, with a spacing of 0.12 meters between them. These configurations are the starting point, simulations will be used to determine the optimal placement and size of the chambers for achieving the best noise reduction performance within the limited space.
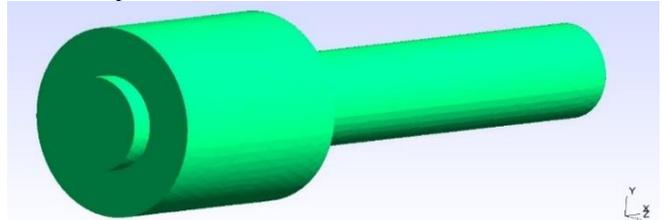

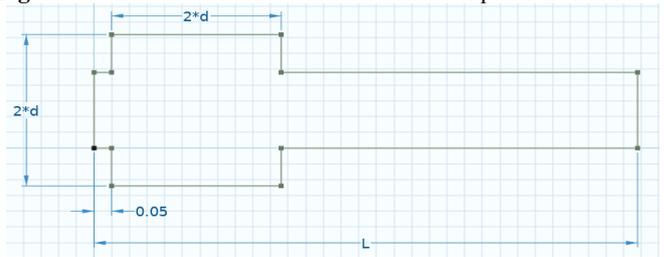**Fig. 13 :** 3-D Model of APU exhaust with one expansion chamber

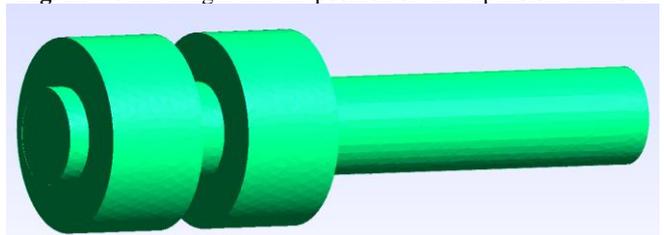**Fig. 14   :** The length and the position of the expansion chamber

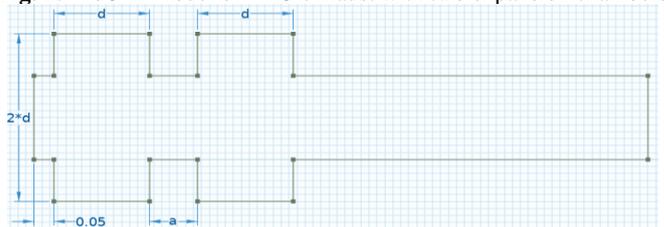**Fig. 15   :** 3-D Model of APU exhaust with two expansion chambers

Fig. 16   : The length and the position of the two expansion chambers

7. Numerical Simulation Of Different Models Of Exhaust Pipe

1. Boundary Conditions

The boundary conditions implemented in this numerical model are of four different types, that takes into account the propagation of the sound wave and the pressure difference between the inside and outside of the pipe. The following table below (TABLE 1) summarizes the various boundary conditions used [9]. The open end of the pipe is modelled by adding an end impedance property. This is an engineering relation for the case of a pipe of circular cross section ending in free space (not flanged pipe).

TABLE 1 : Applied Boundary Conditions

Boundary	Discerption and Value
Sound Hard Boundary (wall)	The normal component of the acceleration (and thus the velocity) is zero –Neumann condition; $\frac{dp}{dn}\|_w = 0$ (normal velocity $v_n = 0$), zerogradient on walls.
Acoustic Pressure	a constant acoustic pressure p_0 is specified and maintained at the boundary, Dirichlet condition; $p= p_0$, fixedvalue.
Inlet	Type: fixedValue , Pressure: barometric pressure (0.975 bar).
Outlet	Type: acousticWaveTransmissive Advective speed: speed of sound (347.62 m/s). Impedance: Specifies how sound interacts with a boundary (edge or surface), Impedance = ρc = (1.2

kg/ m^3)(347.62 m/s) = 417.144 N s m-3

2. The Mesh Settings

The tetrahedral mesh is applied to the whole domain, triangular elements automatically generated on surfaces in 3-D meshes, even when using free tetrahedral elements. In this case, geometry and mesh both generated by Gmsh and export to case file. Gmsh is a 3D finite element mesh generator with built-in pre- and post-processing facilities.

3. Solve Selection

OpenFOAM offers a range of specialized solvers, each specifically designed for specific problem. This approach provides flexibility and efficiency but requires users to carefully select the right solver for their simulation. For Transient solver, turbulent flow of compressible fluids for HVAC and similar applications rhoPimpleFoam solver can be used [10]. By combining the capabilities of rhoPimpleFoam for fluid flow simulation and acoustic modeling techniques like Curle's analogy, it is possible to effectively simulate noise reduction in exhaust pipes.

8. Results and Discussion

Acoustic pressure and sound pressure level (SPL) are key terms used to describe sound and noise characteristics. The Acoustic Pressure describes the local variation in pressure caused by a sound wave, imagine sound waves as a series of compressions (high pressure) and rarefactions (low pressure) of air molecules and higher acoustic pressure fluctuations correspond to higher SPL values, indicating louder sounds. SPL is a logarithmic unit expressing sound intensity relative to a reference pressure. Lower SPL values indicate quieter sounds. This visualization, along with the colour bar legend, provides valuable insights into the pressure variations within the exhaust system, which are essential for understanding sound wave propagation. Use ParaView or other tools to analyze the results, including sound pressure levels. To analyze the frequency content, Fast Fourier Transform (FFT) is applied to the time-domain pressure data.The next figures illustrates that the pressure fluctuations and SPL within the APU exhaust system at 1500 Hz, this frequency was chosen because its value often coincides with the peak SPL within the APU exhaust noise spectrum, making it a crucial target for noise reduction efforts. The red zones in figure 17 represent the compression regions (high pressure) and blue zones represent the expansion regions (low pressure). The maximum SPL value observed in the system in figure 18 reaches 91 dB. This falls within the range considered loud by humans and exceeds the recommended safe exposure limit of 85 dB for prolonged durations.
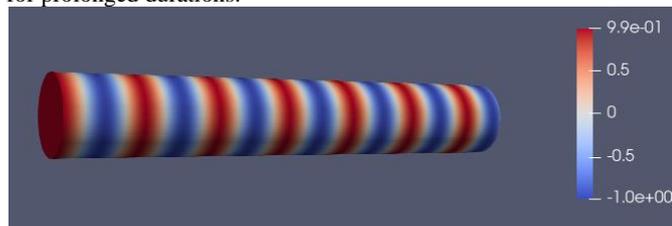

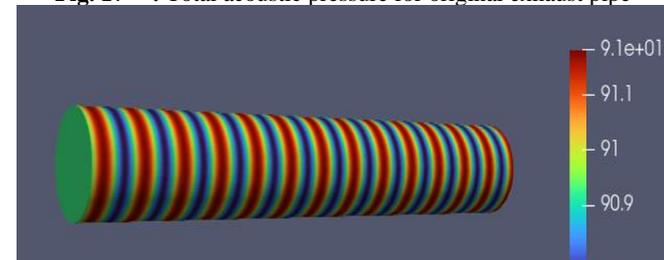**Fig. 17**   : Total acoustic pressure for original exhaust pipe

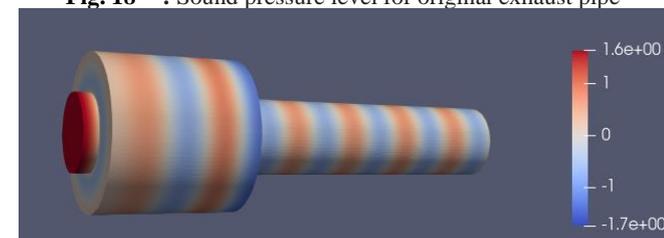**Fig. 18**   : Sound pressure level for original exhaust pipe

Fig. 19   : Total acoustic pressure for exhaust with single chamber
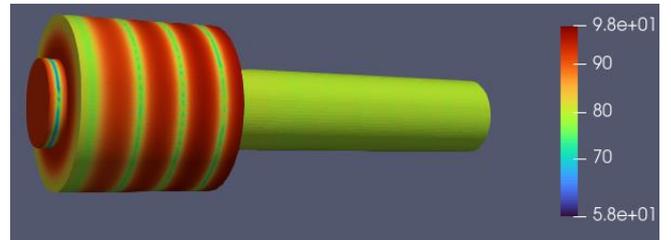

Fig. 20   : Sound pressure level for exhaust with single chamber

The figure 20 indicated a significant reduction in SPL at the exhaust outlet when using the muffler. Compared to the 91 dB SPL observed in the original pipe configuration, the muffler achieved a reduction to about 80 dB. By introducing two expansion chambers, the system's SPL is expected to decrease to below 77 dB (figure 22), which is a substantial improvement compared to the original pipe configuration (exceeding 90 dB). Double expansion chambers achieve noise reduction by exploiting wave interactions within the chambers. As the exhaust gas flows through the chambers, there are areas of pressure reduction (expansion) due to the increased volume. These pressure variations disrupt the propagation of sound waves, leading to lower overall SPL downstream in the exhaust pipe, see figure 23 which show noise level in three configuration.
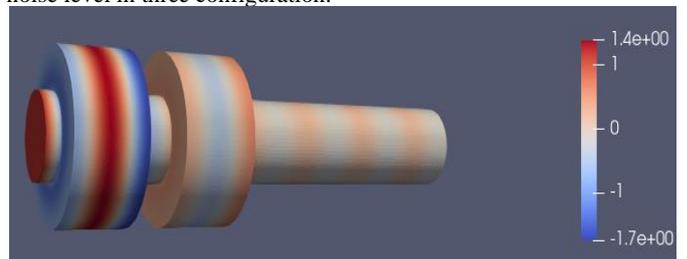

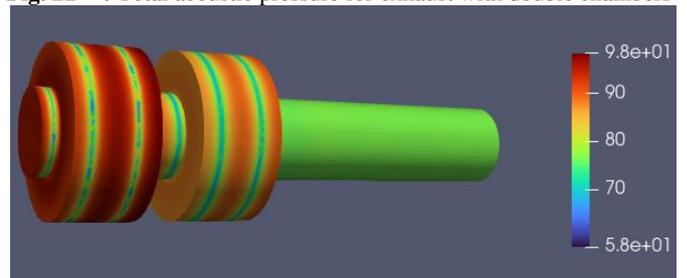**Fig. 21**   : Total acoustic pressure for exhaust with double chambers

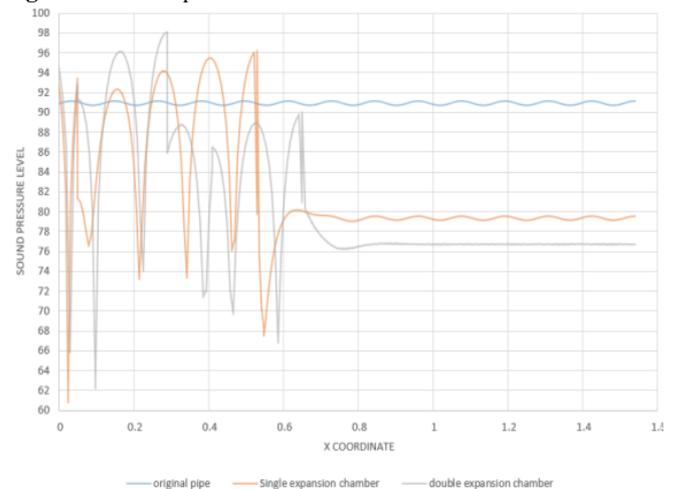**Fig. 22**   : Sound pressure level for exhaust with double chambers

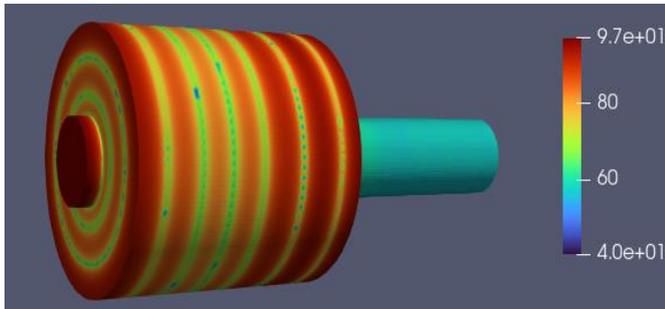**Fig. 23**   :Comparing noise reduction in three exhaust configurations

Fig. 24 : Sound pressure level for exhaust with large volume single chamber
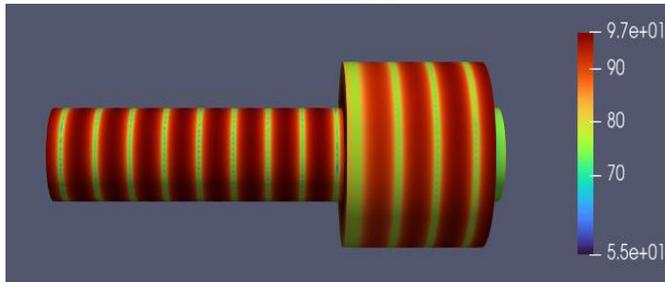

Fig. 25 : Sound pressure level for exhaust with downstream single chamber

Several key factors influence the noise reduction performance of an expansion chamber, Larger chambers in APU exhaust systems significantly reduce noise, By enlarging the chamber volume to a radius 3 times of the pipe radius and a length 3 times of the diameter, the SPL at the outlet decreased to below 57 dB (shown above in figure 24). This is because they allow for more pressure variations that disrupt sound waves. Double chambers can provide even more noise reduction as demonstrated previously, but add complexity. Placement within the exhaust also matters. Simulations showed that (figure 25) moving the chamber further downstream (1 meter from the inlet) led to a lower sound pressure level (75.5 dB) compared to placing it closer to the source (approximately 80 dB).

9. Conclusion and Future Work

In this research, computer simulation is used to redesign APU exhaust pipes, which is considered as one of significant contributor to aircraft noise. The research objectives are not directed only to create a positive ripple effect, benefitting not just airport personnel and surrounding communities, but also the environment itself. With CFD simulation, a significant results are obtained using expansion chambers, which are successfully demonstrated as an effective noise reduction strategy for APU exhaust systems. The results are impactful, revealing a significant noise reduction of up to 14 dB when employing expansion chambers compared to an original pipe design, thus reducing the noise level from approximately 91 dB to 77 dB. Also highlighting the unique challenges associated with APU noise reduction due to size and operational differences. These findings underscores the potential of this approach in creating quieter APU systems. Looking ahead, the recommendations are ordered as:
• Improving the expansion chamber design: optimizing shape and placement for even better noise reduction.
• Validating simulations with experiments: building and testing a real exhaust pipe based on the simulations.
• Exploring alternative noise reduction methods: techniques like perforated pipes or different mufflers.
• Developing lightweight materials: finding new materials or designs to minimize weight and size increases from larger chambers.
 These steps will guide future development of quieter APU exhaust systems, leading to less aircraft noise and a more sustainable aviation industry.

11. References

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